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# Conservation Tillage and Conventional Tillage
## A Comparative Assessment

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by

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Resources for the Future
Washington, D.C. 20036

Grant No. R8060236010

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# FOREWORD

Environmental protection efforts are increasingly directed towards preventing adverse health and ecological effects associated with specific compounds of natural or human origin. As part of this Laboratory's research on the occurrence, movement, transformation, impact, and control of environmental contaminants, management or engineering tools are developed for addressing water quality problems with emphasis on assessing potential exposures to chemical contaminants.

Crop production practices, already significant sources of water and air pollution, represent areas of increasing environmental concern as agricultural demands increase pressures on the nation's land and water resources. This study investigates the comparative economics and environmental impacts of conservation tillage and conventional tillage as a guide to environmental managers.

David W. Duttweiler
Director
Environmental Research Laboratory
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# PREFACE

This report is part of a larger study undertaken at Resources for the Future entitled Resource and Environmental Impacts of Trends in Agriculture in the United States. The larger study originated in concern that emerging long-term trends in demand for U.S. agricultural production, in prices of energy and other key inputs, and in agricultural technologies would put increased pressure on the nation's land and water resources and on the environment. It appeared to us that these trends likely would shift the agricultural situation of the United States from one of chronic surplus to one of recurring if not chronic scarcity. Should such a shift occur the nation likely will require major modification of the policies for resource and environmental management in agriculture which have evolved since the 1930s.

The research reported here was undertaken as a separate study because of the important effects of tillage technologies on the environment. In particular, the strong advantage of conservation tillage relative to conventional tillage in reducing erosion but its possible disadvantage because of increased reliance on pesticides indicated the importance of analyzing prospects for the spread of conservation tillage.

My work in preparing this study was made much easier by the availability of a preliminary report on conservation tillage done by my former colleague at RFF, Jim Mize. He cleared much of the ground I have covered, and I am grateful to him for it.

Pierre Crosson

# ABSTRACT

The objective of this study is to reach a judgment of the amount of U.S. cropland likely to be in some form of conservation tillage in 2010. The future spread of conservation tillage will be conditioned primarily by farmers' perceptions of its economic advantages relative to conventional tillage and by the society's perceptions of its advantages and disadvantages with respect to the environment. Accordingly the study first considers the economics of conservation tillage relative to conventional tillage, examining differences between the two technologies (a) in the quantities of resources used and (b) in yields. The conclusion is that conservation tillage typically uses less of certain resources and more of others, but that on balance it requires 5 to 10 percent less expenditure per acre than conventional tillage. Yield differences vary widely, depending fundamentally upon soil characteristics and climate, but on well drained soils in the Corn Belt, Southeast, and much of the Northern and Southern Plains where weeds can be controlled by herbicides, yields with conservation tillage are fully competitive with yields of conventional tillage. The conclusion is that the economic advantages of conservation tillage could induce farmers to adopt it on 50 to 60 percent of the nation's cropland by 2010. A little less than 25 percent of cropland was in conservation tillage in 1979.

The differences between conservation tillage and conventional tillage with respect to environmental impacts reflect differences in amounts of nutrients delivered to water bodies, in amount of pesticides used, and in amount of erosion generated. Most of the nutrients lost from farmers fields is carried by eroded soil, so losses typically are less with conservation tillage than with conventional tillage. However, little of the nitrogen carried by soil is available to support aquatic plant growth and neither is much of the phosphorus. Moreover, the concentration of available P in soil eroded from conservation-tilled fields tends to be greater than in soil from conventionally-tilled fields. So the erosion advantage of conservation tillage may convey little advantage in reduced delivery to water of available nutrients. Concentrations of nitrate-nitrogen and of available P tend to be higher in runoff from conservation-tilled fields than from conventionally-tilled fields. However, the amount of runoff is usually less from conservation-tilled fields. One consequence of reduced runoff with conservation tillage is increased delivery of nitrate-N through leaching to groundwater and through sub-surface drainage to surface water.

Because of the various counteracting tendencies of conservation tillage with respect to delivery of nutrients to water no firm generalization about the net outcome of these tendencies is warranted.

Conservation tillage typically requires more herbicides and often more insecticides than conventional tillage. We expect changes in insect management technologies in cotton and corn (by far the main users of insecticides) and in the regional location of cotton production to sharply

reduce total and per acre use of insecticides over the next several decades. This reduction will occur even if the spread of conservation tillage tends to increase insecticide use, which is not certain. Herbicide use, however, almost certainly will increase with the spread of conservation tillage. Present evidence does not support the view that the prospective increase in herbicides poses a major threat to the environment. However, the evidence does not cover all possible environmental impacts of herbicides, especially at lower trophic levels. Increased investigation of these more subtle environmental impacts of herbicides is called for.

Prospective increases in land devoted to crop production raise the threat of substantial increases in erosion, with attendant off-farm damages to water quality and to the productivity of the land. These damages will be significantly less if conservation tillage is allowed to expand in response to farmers' perceptions of its economic advantages. The conclusion is that this expansion probably will be permitted to occur, reflecting society's perception that the environmental damages of conservation tillage from herbicides likely will be less than its benefits in reducing erosion.

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# INTRODUCTION

Projections by the author of crop production and yields indicate that harvested cropland in the United States might rise from 342 million acres in 1979 to 440-450 million in 2010 (Crosson and Brubaker). Since little cropland now is held in reserve, most of the additional harvested land would have to come from land now in pasture, forest, range, or wetlands. Land in crops typically produces much more erosion than land in pasture, forest or range, and conversion of wetlands to crops destroys animal habitat. The projected expansion of harvested land, therefore, may imply a substantial rise in environmental damages, represented by increased erosion and loss of the social values of wetlands.

For a variety of reasons the implied increase in environmental damages may not occur. Crop production may not increase as much as projected, or crop yields may increase more. In either case the environmental damages of erosion and conversion of wetlands would be reduced. Even if the projections of harvested land prove accurate, the resulting amount of erosion will be much affected by the amount of land in some kind of conservation tillage. An analysis done by Iowa State University for the study referred to above (Crosson and Brubaker) indicated that, given the projections of harvested cropland in 2010, the nationwide soil losses to erosion by water will be 3.5 billion metric tons (7.4 tons per acre of cropland) if the proportion of cropland in high conservation tillage is 28 percent. If the proportion is 43 percent, however, the amount of erosion by water will be only 2.3 billion metric tons (4.7 tons per acre of cropland).[1]

The spread of conservation tillage, therefore, would reduce the amount of erosion from what it otherwise may be. However, conservation tillage relies more on herbicides for weed control than conventional tillage, and conservation tillage may also require heavier applications of insecticides and fertilizers. Consequently, while the spread of conservation tillage would reduce pressure on the environment from erosion it may increase pressure from use of agricultural chemicals.

Clearly, in thinking about the environmental implicatios of the expansion of agriculture in the United States it is important to consider the likely spread of conservation tillage. That is the purpose of this report. The report is in five parts. The first deals with the problem of defining conservation tillage to distinguish it from conventional tillage. The second part discusses the data showing the amount of land in conservation tillage, for the nation as a whole and for major agricultural regions distinguished by the U.S. Department of Agriculture (USDA). The third part of the report analyzes the economics of conservation tillage systems relative to conventional tillage systems, focusing on differences between the two systems with respect to quantities of resources used and yields. The fourth part assesses the likely environmental impacts of conservation tillage relative to conventional tillage, particularly with respect to erosion, fertilizers and pesticides. The fifth part of the report makes some rough projections of the percentage of harvested land in some form of conservation tillage in 2010, drawing on the economic analysis of part three and on judgments about policy responses to the environmental problems discussed in part four.

---

[1] In the Iowa State model "high" conservation tillage means that crop residue is left on the soil surface year around and the moldboard plow is not used.

# CONCLUSION AND RECOMMENDATIONS FOR RESEARCH

The principal conclusion is that present economic advantages of conservation tillage relative to conventional tillage will induce farmers to use some form of conservation tillage on 50 to 60 percent of the nation's cropland by 2010. (The figure in 1979 was a little less than 25 percent.) Environmental considerations also should favor the spread of conservation tillage, its advantage relative to conventional tillage in reducing erosion being greater than its disadvantage in increased use of chemicals, especially herbicides.*

The study suggests there would be high social payoff to two main lines of research: (1) that designed to increase the economic advantages of conservation tillage relative to conventional tillage, making conservation tillage even more attractive to farmers than at present; and (2) that designed to investigate the more subtle environmental effects of herbicides and to develop weed management practices which ameliorate these effects should they prove more threatening than now seems to be the case.

## RESEARCH TO INCREASE ECONOMIC ATTRACTIVENESS

The study shows that even if conservation tillage spreads to 50 to 60 percent of the nation's cropland by 2010, the expansion of cropland in response to rising export demands likely will significantly increase erosion compared to 1977. Encouraging even wider spread of conservation tillage may be the most cost effective way of reducing the erosion threat, although the cost of this alternative relative to others, e.g., terracing or contouring, was not explored in this study. The principal factors now limiting the spread of conservation tillage are problems of controlling weeds, particularly perennials, with presently available herbicides, and problems of getting competitive yields in poorly drained soils. Research to overcome these problems would expand the area on which farmers could economically adopt conservation tillage. Much of the research to develop more effective herbicides likely will and should be done by the private manufacturers of these materials. Research to overcome problems of poorly drained soils, however, likely would fall in the public domain. The reasons for the unsatisfactory yield performance of conservation tillage on these soils are not completely understood, but there is evidence that poorly drained soils may favor root disease organisms, and soil wetness generally slows mineralization and may promote denitrification. In addition, wetter soils take longer to warm in the spring, thus slowing seedling emergence with possible negative effects on yields. Better understanding of these, and possibly other unfavorable yield effects of wet soils, would suggest measures to overcome these problems. However, it likely would be difficult for private firms to capture enough of the payoff to research along these lines to justify their undertaking it, at least on the socially desirable scale. Consequently, the main burden of such research likely would have to be assumed by publicly financed research institutions.

---

*For a summary of the arguments underlying these conclusions see the preface.

## RESEARCH ON ENVIRONMENTAL EFFECTS OF HERBICIDES AND HERBICIDE ALTERNATIVES

The literature review reported in this study indicates that some important paths by which herbicides may affect the environment have not been much investigated. Impacts at the lower trophic levels in particular have not been adequately explored. A policy to encourage the spread of conservation tillage should include expanded research on these impacts. In addition, as insurance against the possibility that these impacts may turn out to pose unacceptable environmental threats, research should be undertaken to find alternatives to herbicides (other than cultivation) for weed control. For example, development of allelopathy in main crops may eventually have high payoff as a substitute for herbicides (Wittwer, 1980). More generally, it may make sense to broaden the concept of integrated pest management, now largely defined to mean development of alternatives to insecticides for insect control, to include weed management practices which rely less on herbicides. Along this line, researchers at Pennsylvania State University, Cornell, and the University of Delaware are experimenting with ground covers, e.g., a hairy vetch following corn in Delaware, which compete weakly with the main crop but give good control of weeds which would be strong competitors.*

Research to develop alternatives to herbicides may eventually have high economic payoff, but the main reason for undertaking it would be to reduce the risk of environmental damages from herbicides. Consequently, such research should be primarily a public responsibility.

---

*Correspondence with Richard Harwood, Organic Gardening and Farming Research Center.

## DEFINITION OF CONSERVATION TILLAGE

There is no precise, commonly accepted definition of conservation tillage, as the following quotations indicate:

> Conservation tillage includes tillage systems that create as good an environment as possible for the growing crop and that optimize conservation of our soil and water resources, consistent with sound economic practices. Conservation tillage is synonymous with maximum or optimum retention of residues on the soil surface and the utilization of herbicides to control weeds where tillage is not or cannot be performed (Wittmuss, Triplett and Greb).
>
> Chisel-plow, no-tillage, and other tillage systems that leave a protective mulch of crop residues at the surface are often called conservation-tillage systems (University of Illinois).
>
> Conservation tillage: Any tillage system which reduces loss of soil or water compared to unridged or clear tillage (Soil Conservation Society of America).
>
> Conservation tillage systems are tillage systems in which plant residue or a rough soil surface is used to help protect the soil from wind and water erosion (Siemens and Oschwald).

In the wheat growing areas of the northern and southern Great Plains conservation tillage commonly means "stubble-mulching," a wheat-fallow rotation in which the wheat stubble is left on the fallow land to reduce wind and water erosion and conserve soil moisture (Fenster, Unger, Wiese and Allen).

The common element running through these various definitions of conservation tillage is the presence of crop residues on the soil surface to reduce water and wind erosion, and in the Great Plains to increase retention of soil moisture. The amount of crop residue may vary widely, but it must be enough to significantly reduce erosion compared to tillage systems which bury or remove the residue. An implication of the maintenance of crop residues on the soil surface is that conservation tillage systems disturb, or invert the soil less than systems that bury or remove the residue. Since the moldboard plow will bury most crop residue, conservation tillage does not use this implement, and this sometimes is taken as the principal difference between conservation tillage and "conventional" (i.e. moldboard plow) tillage. As the quotation from Wittmuss, Triplett and Greb indicates, conservation tillage relies more on herbicides and less on cultivation for weed control than conventional tillage.

The importance of surface residue to successful employment of conservation tillage systems means that such systems likely will be adopted more widely on crops which produce relatively much residue, e.g. corn and small grains, than on crops leaving relatively little residue, e.g., soybeans and cotton. Clearly, the amount of residue left is a factor, but it must be considered in the context of all other relevant factors. A substantial amount of land in soybeans is conservation tilled, despite the relatively small amount of residue with this crop, because of advantages for double-cropping following a small grain, which does leave relatively much residue. Not much cotton land is in conservation tillage, but problems of controlling weeds with herbicides are probably as limiting as the small amount of residue.

No-tillage systems are a polar case of conservation tillage. No-tillage has been concisely defined as "...placing the crop seed or seed transplant into the soil by a device that opens a trench or slot through the sod or previous crop residue only sufficiently wide or deep to receive the seed or transplant roots and to provide satisfactory seed or root coverage. No other soil manipulation is required. Weeds are controlled by herbicides, crop rotation, and plant competition" (Young). The "device referred to is a narrow chisel point, a fluted coulter or an angled disk.

The literature often does not distinguish clearly between no-till and other forms of conservation tillage, and our discussion generally follows the literature in this respect. No-till accounts for a small proportion of all land in conservation tillage, and the amount has not increased much in recent years (see Table 2). This suggests that the potential for no-till, with presently available herbicides and seed varieties, is more limited than for other forms of conservation tillage. We state this, however, only as a hypothesis which we have not been able to pursue in this study.

In the literature reduced tillage is sometimes used as a synonym for conservation tillage, a practice avoided in this report. Reduced tillage may mean merely that a farmer who previously made 10-12 passes over his field in the course of a season, perhaps in response to higher fuel costs, now makes only 8-10. His principal tillage implement may still be the moldboard plow with all residue plowed under or removed. The farmer may increase applications of herbicides to substitute for one or two cultivations, but otherwise his tillage practices are unchanged and the amount of erosion from his fields unaffected.

Minimum tillage also is frequently used in the literature as a synonym for conservation tillage. The Resource Conservation Glossary defines minimum

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tillage as "that amount of tillage required to create the proper soil condition for seed germination and plant establishment" (Soil Conservation Society of America), a definition so general as to be virtually useless. The No-Till Farmer defines minimum tillage as "limited tillage, but where the total field surface is still worked by tillage equipment," also quite a general definition (No-Till Farmer, March 1979). However, Frank Lessiter, editor of the No-Till Farmer, stated in conversation with the author that the No-Till Farmer's definition of minimum tillage refers to tillage systems which do not use the moldboard plow, which leave enough crop residue on the soil surface to significantly reduce erosion, and which rely primarily on herbicides for weed control. Since these are the principal characteristics of conservation tillage as defined in this report, we take the No-Till Farmer's definition of minimum tillage as substantially, although perhaps not identically, the same as our definition of conservation tillage.

Table 1 gives the key characteristics of conservation tillage which distinguish it from conventional tillage, as those terms are used henceforth in this report.

TABLE 1. DISTINGUISHING CHARACTERISTICS OF CONSERVATION TILLAGE AND CONVENTIONAL TILLAGE

| Characteristic | Tillage System | |
|---|---|---|
| | Conservation | Conventional |
| Tillage instrument | Not the moldboard plow | Moldboard plow |
| Crop residue on soil surface | Enough to significantly reduce erosion | Little or none |
| Weed control | Primarily herbicides, but may also cultivate | Mechanical cultivation more important than with conservation tillage, but herbicides typically used also |

## LAND IN CONSERVATION TILLAGE

Table 2 gives estimates of the amount of land in conservation tillage in various years. The explanation for the differences between the USDA and No-Till Farmer estimates is not clear. According to Gerald Darby, who provided

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## TABLE 2. LAND IN CONSERVATION TILLAGE IN THE U.S.

(millions acres)

| | USDA | % of Harvested Cropland | No-Till Farmer | | | % of Harvested Cropland |
|---|---|---|---|---|---|---|
| | | | No-Till[a] | Minimum Till[b] | Total | |
| 1965 | 6.6 | 2.3 | NA | NA | NA | NA |
| 1973 | 29.5 | 9.3 | 4.9 | 39.1 | 44.0 | 13.9 |
| 1975 | 35.8 | 10.8 | 6.5 | 49.7 | 56.2 | 17.0 |
| 1976 | 39.2 | 11.8 | 7.5 | 52.1 | 59.6 | 18.0 |
| 1977 | 47.5 | 14.1 | 7.3 | 62.7 | 70.0 | 20.7 |
| 1978 | 51.7 | 15.6 | 7.1 | 67.7 | 74.8 | 22.6 |
| 1979* | 55.0 | 16.1 | 7.6 | 71.6 | 79.2 | 23.2 |

*Preliminary.

[a] Defined as "where only the intermediate seed zone is prepared. Up to 25 percent of surface area could be worked. Could be no-till, till-plant, chisel plant rotary strip tillage, etc. Includes many forms of conservation tillage and mulch tillage." Obviously the numbers in this column reflect tillage practices other than no-till.

[b] Defined as "limited tillage," but where the total field surface is still worked by tillage equipment.

Sources: USDA, from Gerald Darby, conservation agronomist with the Soil Conservation Service. Based on reports from SCS county field offices.

No-Till Farmer, March 1979, pp. 4-5. Estimates by State agronomists of the Soil Conservation Service.

Harvested Cropland 1965-1978 from USDA, Jan. 1980. 1979 from Tom Frey, USDA.

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the USDA estimates, the differences are not explained by differences in definition of conservation tillage. Although Soil Conservation Service (SCS) people are the source of both sets of data, they are not the same people. Those providing the estimates to the No-Till Farmer are state resource agronomists, conservationists, or other state technical staff persons, while the USDA estimates are based on reports from county-level SCS people.

While the two sets of estimates differ in amount of land in conservation tillage, they agree in showing that the amount increased sharply from the early 1970s, both in absolute terms and as a percentage of all harvested cropland. For speculating about the future expansion of conservation tillage, the agreement regarding past growth probably is more important than the difference about present amount.

Table 3 shows the No-Till Farmer estimates of land in conservation tillage by USDA regions in 1978 and 1979. Land in conservation tillage as a percent of total cropland harvested in each region also is shown. Between them the Cornbelt and Northern Plains account for almost 60 percent of the land in conservation tillage. These two regions also are among the most important in terms of the percentage of harvested cropland in conservation tillage, although in this respect Appalachia and the Southeast are of equal importance.

The rapid spread of conservation tillage in the last ten to fifteen years is attributable to its market-determined economic advantages relative to conventional tillage. While the Soil Conservation Service and other conservation organizations have encouraged the spread of conservation tillage, they have done it mostly by exhortation and education. Some cost-sharing funds have been available to encourage adoption of conservation tillage, but the amounts have been relatively small. Beginning in 1980 funds available through the Rural Clean Water Program could be used to provide incentives to farmers to adopt conservation tillage systems. However, the total available for all purposes under the RWCP was only $50 million, and in any case this program could not have affected the spread of conservation tillage prior to 1980. Support for conservation tillage under the RCWP or similar programs may strengthen in the future, but the future spread of the technology likely will continue to depend in large measure on its economic attractiveness to farmers relative to conventional tillage as determined by market forces.

## ECONOMICS OF CONSERVATION TILLAGE RELATIVE TO CONVENTIONAL TILLAGE

The objective of this section is to arrive at a judgment about the average costs (costs per unit of production) of conservation tillage relative to conventional tillage. Ideally this would be done by way of analysis of the two technologies as used on main crops under representative soil and climatic conditions around the country. One possibility along this line would be detailed farm budget studies which would capture the cost differences

## TABLE 3. CONSERVATION TILLAGE BY REGION

| | 1978 | | 1979 | |
|---|---|---|---|---|
| | Millions Acres | % of Cropland harvested | Millions Acres | % of Cropland harvested |
| Northeast | 2.23 | 17.2 | 2.40 | 18.2 |
| Lake states | 6.78 | 18.2 | 6.93 | 17.9 |
| Corn Belt | 20.33 | 24.6 | 21.73 | 28.7 |
| Northern Plains | 23.65 | 32.2 | 25.01 | 33.3 |
| Appalachia | 5.42 | 29.8 | 5.83 | 30.7 |
| Southeast | 4.55 | 31.4 | 5.09 | 33.5 |
| Delta | 1.26 | 6.7 | 1.36 | 7.0 |
| Southern Plains | 2.24 | 7.5 | 1.98 | 6.1 |
| Mountain | 6.31 | 24.6 | 6.43 | 24.8 |
| Pacific | 1.90 | 10.9 | 2.35 | 13.5 |
| Total | 74.67 | 22.6 | 79.11 | 23.1 |

Sources: Land in conservation tillage from No-Till Farmer, March 1979.

Cropland harvested: 1978 from USDA, Jan. 1980; 1979 from Tom Frey, USDA.

The No-Till Farmer estimates that in both 1978 and 1979 the sum of land in no-tillage, minimum-tillage and conventional tillage in the country as a whole was 300 million acres. The USDA (Jan. 1980) shows 331 million acres of cropland harvested in 1978 and 342 million acres in 1979. If some of the "missing" cropland were in conservation-tillage, the figures in the table would be too low.

between the two technologies under the variety of conditions in which they actually are used by farmers. Examples of such studies are those by Walker and by Doster and Phillips, cited subsequently in this report.

The resources available for this study were wholly inadequate for this detailed approach. Instead we have relied upon a survey of the literature on tillage technologies, supplemented by interviews with knowledgeable people. We have sought information about differences between the two technologies in quantities of resources used per acre and in yields, since these are the factors determining average costs.

## QUANTITIES OF RESOURCES

The resources considered are labor, machinery and equipment, fuel, fertilizers, pesticides, and management.

### Labor

Much of the literature on tillage systems is silent on the question of labor requirements for conservation tillage relative to those for conventional tillage. Wherever the question is treated, however, there is overwhelming agreement that less labor per acre is needed with conservation tillage than with conventional tillage. The reason is that with conservation tillage the labor saved by reducing the number of passes over the fields is more than enough to offset any additional labor required by increased applications of chemicals for weed, insect or disease control. Most, if not all of the labor saved with conservation tillage is in pre-harvest activities. Of course the labor saved will confer no advantage on conservation tillage unless the labor has some productive alternative use or has value to the farmer as increased leisure time.

While the literature is virtually unanimous that conservation tillage requires less labor than conventional tillage, estimates of the amount of the difference are highly variable. Our survey of the literature produced the estimates shown in Table 4. As noted earlier, most of the literature we reviewed had no references to labor requirements. The estimates in Table 4 vary from 1.25 (conventional tillage requiring 25 percent more labor than conservation tillage) for spring wheat in southern Alberta up to 3.0 for unspecified conditions with respect to crop or location. Most of the estimates, however, fall between 1.7 and 2.5. The sources do not state explicitly that the same kinds of labor are used with both tillage systems, but internal evidence indicates that is the case. (However, conservation tillage requires more management skill than conventional tillage. This is dealt with below.)

The importance of the difference in labor requirements depends upon how important labor costs are in total costs, exclusive of the cost of land. (We assume that land costs are not affected by the choice of tillage technology.) For corn, wheat, grain sorghum, soybeans and cotton, total (not just pre-harvest) labor costs in 1979 varied from 8.0 percent of total costs exclusive of land costs in corn to 11.8 percent in grain sorghum (USDA, June

## TABLE 4. ESTIMATES OF QUANTITY OF LABOR REQUIRED PER ACRE IN CONVENTIONAL TILLAGE RELATIVE TO CONSERVATION TILLAGE[a]

| Comment | Ratio, Conventional-till to Conservation-till | Sources |
|---|---|---|
| No-till, crop or other details not specified | As much as 3.0 | Triplett & Van Doren, Jan. 1977 |
| Data for 1969, area not specified | | USDA, May 1975 |
| Corn | 2.1 | |
| Sorghum | 2.1 | |
| Soybeans | 2.4 | |
| Cotton | 2.4 | |
| Irrigated winter wheat, area not specified | | Allen, Musick & Wiese |
| No-till | 2.0 | |
| "Limited"-till | 1.4 | |
| Corn in Nebraska | 2.0 | Derscheid, Durland & Shubeck |
| Corn in Michigan | 1.7 | Mannering and Burwell |
| Corn in central Indiana | | Doster and Phillips |
| Chisel plow | 1.6 | |
| Till-plant | 2.5 | |
| No-till | 2.3 | |
| Corn in Piedmont of North Carolina | 2.7 | Doster and Phillips |
| Dryland continuous grain sorghum, Texas Panhandle | 1.6 - 1.7 | Shipley and Osborn |
| Dryland wheat-grain sorghum rotation, Texas Panhandle | 1.75 | Shipley and Osborn |
| No-till, spring wheat in southern Alberta | 1.25 - 1.40 | Zentner and Lindwall |

[a] We assume the differences refer to pre-harvest labor requirements. The literature is not always clear on this.

Note: Erbach, Lovely, and Ayres, received too late for detailed consideration in this study, show that labor required for conventional tillage of corn exceeded that required by various conservation tillage systems by only 30 to 50 percent. However, the estimates of Erbach et al evidently are total labor required. Most estimates in this table apparently are only for pre-harvest labor.

15, 1979). Clearly, the savings in labor resulting from a shift to conservation tillage from conventional tillage would have relatively little effect in reducing costs. The effect on profits, however, could be substantial, particularly when profit margins are small. For example, in 1979 farmers received an average price of $2.41 per bushel for corn and average corn yields were 109.4 bushels per acre (USDA, April 1980), indicating gross revenue per acre of $264 for corn. Total costs per acre were $223 (including land costs), and labor costs were $13 per acre.[2] A farmer who shifted from conventional tillage of corn to conservation tillage could expect to reduce his labor costs by about one-half. Assuming for purposes of this illustration that all other costs remained the same, and yields of the two tillage systems also were the same, the shift in tillage practices would save the farmer $6.50 and reduce his total costs only 3 percent. However, his profit margin, $41 per acre with conventional tillage, would rise to $47.50, an increase of 16 percent.[3] For the farmer considering whether to switch to conservation tillage, the effect on profits of course is what counts.

## Equipment

The USDA's survey of conservation and conventional tillage technologies states that data on machinery investment costs for the two classes of technology are meager, scattered and specific to types, location and size of farm, making them inadequate for deriving conclusions about the amounts of these costs relative to one another (USDA, May 1975).

Our survey of the literature supports the statement that the data on machinery and equipment costs are fragmentary. However, these data are almost unanimous in showing that these costs are less with conservation tillage than with conventional tillage.[4] The reasons for this, however, usually are not stated. Wittmuss, Triplett, and Greb assert that direct planting into untilled soil requires less power than conventional tillage so a smaller, and less expensive tractor will suffice with conservation tillage [5] (Wittmuss, Triplett, and Greb refer specifically to no-tillage systems). We have not seen this stated, but it is plausible that tractor maintenance costs also would be less with conservation tillage since with this system the farmer makes less frequent use of his tractor than with conventional tillage.

---

[2] USDA, June 15, 1979. Land costs are calculated on average acquisition value.

[3] This overstates the potential increase in profits from a shift to conservation tillage for two reasons: (1) it assumes that the cost figures reflect only conventional tillage when in fact a significant amount of corn land already is in conservation tillage; (2) it assumes that total labor requirements are twice as high for conventional tillage as for conservation tillage. In fact, most if not all of the difference is in pre-harvest labor requirements.

Estimates of the differences in machinery investment costs between conventional tillage and conservation tillage vary widely, as Table 5 shows. The data are not comparable among the various sources cited in the table; for example, the estimates by Doster and Phillips are only for machinery which differs among the tillage systems, while those by Walker include the full component of machinery used with each system. With the exception of some of the estimates by Siemens and Oschwald for a 500-acre farm, however, the table demonstrates that conservation tillage has a clear advantage over conventional tillage with respect to machinery investment costs.

This judgment applies to situations in which farmers convert entirely to conservation tillage. Some observers think, however, that many farmers who adopt conservation tillage will want to maintain the capacity to use conventional tillage every few years to reduce weed problems and to deal with soil compaction, which can become a problem with conservation tillage, or because they have a variety of soils, some well adapted to conservation tillage and others not. For farmers who adopt this strategy machinery

---

[4] Erbach, Lovely, and Ayres for corn in the Cornbelt; Griffith, Mannering, and Moldenhauer with respect to the eastern Cornbelt; Walker on southwestern Iowa; Derscheid, Durland, and Shubeck on South Dakota; University of Illinois on Illinois; Siemens on the Cornbelt; R. E. Phillips, Blevins, Thomas, Frye, and S. H. Phillips, area not specified, but presumed here to be generally applicable; Triplett and Van Doren (Jan., 1977), general; Zentner and Lindwall, southern Alberta; Taylor, Reneau, and Trimble, Bushland, Texas and Rio Grande Valley, Texas; Doster and Phillips on central Indiana; Shipley and Osborn on arid and semiarid regions of the United States. Siemens and Oschwald on Illinois showed that on 202 hectares of corn-soybean land four of six conservation tillage systems had higher machinery costs than conventional tillage. On 404 hectares, however, only one of the six conservation tillage systems had higher machinery costs. This is the only instance we have found of some conservation tillage systems having higher machinery costs than conventional tillage.

[5] However, in conversation with the author, Albert Trouse, Jr., soil scientist with the USDA's National Tillage Machinery Laboratory, Auburn, Alabama, stated that on heavily compacted soils no-tillage will have to be alternated from time to time with sub-soiling to a depth of 12"-14", an operation needing a more powerful, more expensive, tractor than is needed with conventional tillage.

## TABLE 5. ESTIMATES OF MACHINERY COSTS FOR CONVENTIONAL AND CONSERVATION TILLAGE

(dollars per acre)

| | Conventional | | Conservation | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Source | Fall plow | Spring plow | Chisel | Partial Chisel | Disk Chisel | Coulter Chisel | Disk | Till plant | Limited | No-till | Minimum till |
| Siemens & Oschwald[a] | | | | | | | | | | | |
| 500 acres | 30.76 | 29.35 | 29.65 | 31.10 | 32.76 | 33.05 | 25.21 | | | 24.82 | |
| 1000 acres | 24.56 | 24.71 | 22.08 | 24.86 | 19.91 | 21.52 | 20.07 | | | 16.66 | |
| Doster & Phillips[b] | 8.22 | 13.36 | 8.38 | | | | | 6.16 | | 6.40 | |
| Taylor, Reneau and Trimble | | | | | | | | | | | |
| Furrow irrigated winter wheat[c] | 10.84 | | | | | | | | 8.24 | 6.29 | |
| Dryland grain sorghum[d] | 14.86 | | | | | | | | 8.97 | 5.17 | |
| Walker[e] | 31.89 | 41.88 | | | | | | | | | 29.56 |

[a] Corn and soybeans in Illinois.

[b] Corn in central Indiana, 600 acre farm.

[c] Bushland, Texas, size of farm not given. Based on average yields 1971-72/1973-74.

[d] Rio Grande valley, Texas, size of farm not given. Based on average yields 1974-76.

[e] Southwest Iowa, corn-corn-soybean rotation, 320 acre farm.

Note: The data are not comparable among sources.

investment costs likely would be greater than if they went completely to conservation tillage.[6] However, for these farmers a less expensive alternative to the additional investment in machinery may be to custom hire conventional tillage whenever needed.

It appears, therefore, that for many farmers conservation tillage may be viewed as complementary to conventional tillage rather than as a substitute. Without information about the relative number of such farmers it is not possible to judge the importance of machinery investment costs in the spread of conservation tillage.

## Fuel

The literature is unanimous that conservation tillage requires less preharvest fuel than conventional tillage because of fewer passes over the field.[7] As in the cases of labor and machinery investment costs, estimates of fuel savings vary, as indicated in Table 6. In addition to the data in the table the literature reveals the following:

Because of the elimination of plowing and disking (and reduced machinery manufacture) no-till saves the equivalent of about 3.9 gallons of diesel fuel per acre compared to conventional tillage (Phillips et al.).

Fuel and other machinery-related costs are less with conservation tillage than with conventional tillage (University of Illinois).

Per-acre costs of fuel (and machinery repairs) on a 600-acre farm in central Indiana were:

| | |
|---|---|
| Conventional tillage | |
| Fall plow | $ 2.18 |
| Spring plow | 2.00 |
| Chisel plow | 1.85 |
| Till-plant | 1.30 |
| No-till | 1.44 |

(Doster and Phillips).

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[6] University of Illinois. In discussion between the author and Robert Pope, Joseph Downs, Earl Swanson and Malcolm Shurtleff, all of the University of Illinois, the point was made that many farmers likely would want to maintain the capacity for both conventional and conservation tillage. Howard Doster and William Miller, Purdue University, in discussion with the author, also took this position.

[7] This statement refers to fuel used on the farm, not to the total energy requirements of conservation tillage and conventional tillage. The energy advantage of conservation tillage because of lower on-farm fuel requirements is at least partially offset by the greater amount of energy embodied in increased herbicide requirements.

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## TABLE 6. FUEL REQUIREMENTS FOR CONVENTIONAL TILLAGE AND CONSERVATION TILLAGE

(gallons diesel fuel per acre)

| Source: Allen, Musick & Wiese | Gals. per acre | Comment |
|---|---|---|
| Tillage system | | Furrow irrigated continuous wheat, southern High Plains |
| Conventional | 7.2 | |
| Limited-till | 4.4 | |
| No-till | 2.8 | |
| Source: Wittmuss, Olson & Lane | | Corn |
| Tillage system | | |
| Conventional | 4.06 | |
| Disk & plant | 1.64 | |
| Till-plant | 1.51 | |
| No-till | 1.07 | |
| Source: USDA, May 1975 | | Crop not specified |
| Tillage system | | |
| Conventional | 5.33 | |
| Till plant | 2.46 | |
| No-till | .90 | |
| Source: Derscheid, Durland & Shubeck | | Corn in South Dakota. Fuel is gasoline, not diesel. |
| Tillage system | | |
| Conventional | 5.6 | |
| Reduced-till | 4.5 | |
| No-till | 2.9 | |

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In southern Alberta in a two year wheat-fallow rotation, no-till required 57.9 percent as much fuel and oil as conventional tillage. In a three year rotation the no-till requirement for fuel and oil was 71.9 percent of the conventional tillage requirement (Zentner and Lindwall).

A study of fuel consumption of tillage systems under Oklahoma conditions showed that conservation tillage saved 1 to 3 gallons of diesel fuel per acre relative to moldboard plow farming (American Society of Agronomy).

In southwestern Iowa in a corn-corn-soybean rotation fuel costs per acre were $2.33 with conventional spring plow tillage, $2.50 with conventional fall plow tillage and $.96 with conservation tillage (Walker).

Triplett and Van Doren (Jan. 1977) assert that conventional tillage requires the equivalent of 2.9 to 3.6 gallons of diesel fuel per acre compared to .4 gallons per acre for no-till.

These various numbers suggest that no-till requires 3 to 4 fewer gallons per acre of diesel fuel equivalent than conventional tillage, and that for other kinds of conservation tillage the saving is on the order of 1 to 3 gallons. The maximum savings per acre for conservation tillage, therefore, is approximately $4.50, assuming the price of diesel fuel is $1.10 per gallon. In 1979 the per acre costs of fuel and lubrication for cotton, corn, grain sorghum, wheat and soybeans varied from $5.57 for wheat to $12.85 for cotton. As a percentage of total costs (excluding land) fuel and lubrication costs for these crops varied from 4.6 for cotton to 9.4 for grain sorghum (USDA, June 15, 1979). Fuel and lubrication costs for corn were $9.02 per acre. As indicated above in the discussion of labor costs, the difference for corn production between average gross revenue per acre and total per acre costs was $41. The data for fuel costs suggest that by shifting from conventional tillage to no-till the "average" corn farmer could have increased this difference to $45.50, or by about 11 percent. By shifting to some other form of conservation tillage the fuel saving would have increased the difference a maximum of about $3.30, or 8 percent. These estimates reflect the same assumptions and should be taken with the same caveats as in the discussion of the savings in labor costs obtained by shifting to conservation tillage in corn (see especially footnote 3).

## Fertilizer

There are differing views in the literature as to whether conservation tillage and conventional tillage have different requirements for fertilizer. One of the problems of assessing the literature on this point is that the concept of fertilizer "requirements" often is not clearly defined. From the farmer's standpoint the definition can be assumed to be economic: that amount of fertilizer is "required" which, at the margin, will yield a return just equal to the cost of the fertilizer, making allowance for risk. To be sure the farmer may not define his fertilizer requirements in just these terms, but as a profit maximizer, that is what he has in mind.

We have found no clear definition of fertilizer requirements in the literature, but it is not the economic definition implicitly employed by farmers. It is rather a technical definition reflecting judgments of agronomists and soil scientists of amounts of fertilizer needed under given conditions of soil type, structure, temperature, moisture, and available nutrients. Often the yield responses to the fertilizer "requirements" of conservation tillage and conventional tillage are not given. Clearly, if conservation tillage "requires" more fertilizer than conventional tillage, but there is an offsetting increase in yield, the difference in "requirements" has no bearing on farmers' choices between the two types of technology.

What we would like to have for each type of technology is a statement of fertilizer requirements in terms of so much per unit of output for given soil and other technical conditions of production. The relationship between the requirements for each technology might vary with output, but this would present no problems as long as the respective requirements at each level of output were clearly stated.

Since in the literature requirements typically are not stated in this fashion, it is difficult to make firm judgments about the amounts of fertilizer needed with conservation tillage and conventional tillage. Bearing that in mind, there is a commonly expressed view in the literature that under given soil conditions conservation tillage often requires more nitrogen fertilizer than conventional tillage because the cooler and more moist soils with conservation tillage slow the mineralization of nitrogen and promote denitrification (University of Illinois; Fenster; Willis and Ameniya; Ameniya; Griffith, Mannering and Moldenhauer; R. E. Phillips et al.; also John Doran, USDA soil scientist, Lincoln, Nebraska, cited in No-Till Farmer, Oct. 1979; Donald Huber, agronomist, Purdue U., cited in No-Till Farmer, May 1979; Huber also in conversation with the author, Sept. 21, 1979; Robert Pope and Joseph Downs, U. of Illinois in conversation with the author, Sept. 20, 1979). This situation is most likely to occur where soils are "poorly" or not "adequately" drained, but "poorly" and "adequately" are not defined.

Research in Kentucky showed that leaching of nitrate occurs more readily from no-till plots than from conventionally tilled plots (R. E. Phillips et al.). The reason is that no-till reduces evaporation of water (because of surface residue), and leaves undisturbed the channels through which the water, and the nitrate it carries, moves downward.

With conservation tillage fertilizer is applied at or near the soil surface, where it tends to accumulate over time. Nitrogen so applied may cause an increase in the acidity of the top 1 to 2 inches of soil (Griffith, Mannering and Moldenhauer; Reicosky et al.; R. E. Phillips et al.; Triplett and Van Doren, 1969; Harrold, Triplett, and Edwards; American Society of Agronomy). One consequence is to reduce the effectiveness of triazine herbicides, widely used on corn, with adverse effects on weed control and hence on yields. The uptake of nutrients also is reduced as acidity increases (American Society of Agronomy). The acid condition can be corrected by liming. Some sources indicate that more lime would be required to do this (American Society of Agronomy; Triplett and Van Doren, 1969), which of course would add to the fertilizer-associated cost of conservation tillage relative to conventional tillage. Others assert that no more lime but more frequent application of it would control the acid condition (D. R. Griffith, comment on a draft of this study). If more frequent applications of lime require trips across the field that would not otherwise be made, this too would increase fertilizer-related costs of conservation tillage relative to conventional tillage.

In his study of the relative costs of conventional and conservation tillage systems in Iowa, Walker, on the advice of an agronomist at Iowa State University, assumed that in a three-year corn-corn-soybean rotation conventional tillage would require 320 pounds of nitrogen per acre in corn (hence 160 pounds per acre for each year in corn) and conservation tillage would require 360 pounds, or 12.5 percent more than conventional tillage. In a corn-soybeans-corn-oats-meadow-meadow rotation the nitrogen requirement over the entire rotation sequence would be 210 pounds per acre for conventional tillage and 250 pounds per acre for conservation tillage.

The literature is by no means unanimous that conservation tillage requires more nitrogen fertilizer than conventional tillage. R. E. Phillips, et al., while recommending that more nitrogen be applied on no-till corn in Kentucky because of more denitrification, leaching and slower mineralization, nonetheless say they expect this to be offset by higher yields because at recommended rates of application no-till corn uses nitrogen more efficiently than conventional tilled corn. Moschler and Martens, working with corn in Virginia, found that nitrogen efficiency was less with no-till at low levels of application but higher at high levels of application. The highest level of application--an average of 140 pounds per acre per year over three years--was about the same as average applications of nitrogen on corn around the country (135 pounds per acre per year average for the nation, 142 pounds in the Cornbelt, 144 pounds in the Northern Plains).

Allen Bandel, an agronomist at the U. of Maryland, drawing on a 7-year experiment with no-till and conventionally tilled corn in that state, asserts that nitrogen application rates should be the same for both tillage systems (No-Till Farmer, Feb. 1980). Bandel's work is consistent with that of Moschler and Martens in showing that nitrogen efficiency is less with no-till at low levels of application, but is greater at higher levels. The higher levels--160 pounds per acre--are recommended by Bandel, and are roughly 10 to 15 percent higher than typical application rates for nitrogen on corn. In their study of the economics of alternative tillage systems for grain sorghum in the Rio Grande Valley of Texas, Taylor, Reneau and Trimble, drawing on data from the Perry Foundation, assumed that fertilizer requirements per acre were the same for conventional tillage, "limited" tillage and no-till. Wittmus, Olson and Lane also show that nitrogen requirements were the same for conventional and conservation tillage of corn in Nebraska. Shipley and Osborn cite data from a study by Musick of irrigated sorghum following wheat at Bushland, Texas which show no differences in fertilizer requirements between a disk tillage system and a chemical fallow (no-till) system.

Potassium and phosphorus fertilizers tend to accumulate in the top few inches of soil with conservation tillage, but this seems to present no special problems requiring greater applications of potassium and phosphorus. R. E. Phillips et al. report that experimental results showed that potassium availability was about the same with no-till and conventional tillage in Kentucky, while phosphorus was slightly more available with no-till. The rest of the literature reviewed was generally consistent with these findings in that it indicates no reason for believing that P and K requirements would differ much as between conservation tillage and conventional tillage. Should the tendency of P and K to accumulate in the upper soil layer present a problem of deficiency of these nutrients they could be worked deeper by periodic plowing.[8] Of course, this would increase the cost of conservation tillage relative to conventional tillage.

The discussion has dealt with differences in fertilizer requirements of conventional and conservation tillage in a single year. It also is important to consider the long-term effects on soil nutrients of the two tillage systems, i.e., whether they differ with respect to the build-up or draw-down of nutrients over time. Cultivation increases the exposure of the soil to atmospheric oxygen, stimulating the biological activity which decomposes soil organic matter, thus releasing soil nitrogen. For this reason "...minimal or no tillage is expected to conserve N" (Stanford, p. 33). However, the amount of nitrogen held in the soil in organic form is not well correlated with the amount available to the crop (Stanford), so the larger store of soil organic N resulting from conservation tillage does not necessarily mean that over time the amount of applied nitrogen needed with conservation tillage would decline relative to the amount needed with conventional tillage. Indeed, the smaller amount of *available* nitrogen is what leads Doran (*No-Till Farmer*, Oct. 1979) to recommend greater applications of nitrogen with conservation tillage despite the larger amount of nitrogen held in the soil.

Bandel et al., writing in 1975, postulated that "...the N status of soils will gradually increase under no-tillage and gradually decline under continued conventional tillage" (p. 785), although they noted that the processes underlying this postulated difference between tillage systems were little understood. Subsequent cooperative research between the USDA's Biological Waste Management and Soil Nitrogen Laboratory at Beltsville, Maryland, the University of Maryland (Bandel) and the USDA laboratory at Morgantown, West Virginia, led Stanford, a co-author with Bandel of the 1975 piece, to conclude that "Limited evidence suggests that continued no-till culture will result in greater incorporation and retention of applied N than occurs under tillage..." (Stanford, p. 2).

The literature we have reviewed indicates that the effects of conservation and conventional tillage on micro-nutrients have been little studied. According to Griffith, studies of corn tillage systems in Indiana showed that plant uptake of copper, zinc and manganese was less with coulter planting (a form of no-till) than with conventional tillage. There was no evidence, however, that this had reduced yields (Griffith, Mannering and Moldenhauer). Moschler, Martens and Shear reported that the kind of tillage system used had no effect on uptake of calcium and magnesium in corn grown in soils up to 20 cm deep. Between 20 and 40 cm uptake of magnesium was greater with no-till than with conventional till and calcium was the same.

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[8] D. R. Griffith in commenting on a draft of this report.

Judging from our review, the evidence bearing on the relationship of tillage systems to soil micro-nutrients is too thin to warrant firm conclusions about the relationship.

Much of the discussion of the fertilizer requirements of conservation tillage and conventional tillage is based on comparative studies of no-till and conventional-till. This is particularly true of the studies done in Maryland (Bandel et al., Stanford), Kentucky (R. E. Phillips et al.), Ohio (Triplett and Van Doren, 1969), and Virginia (Moschler and Martens). Whether the findings of those studies would apply to the comparision of conventional tillage with other kinds of conservation tillage is uncertain.

In our judgment the literature does not provide the basis for well grounded generalizations about the fertilizer requirements of conservation tillage relative to conventional tillage. This is awkward, particularly for estimating the spread of conservation tillage in corn because fertilizers account for fully 20 percent of the total non-land costs of corn production and one-third of variable costs (USDA, June 15, 1979). The difference, if there is one, between fertilizer requirements for the two tillage systems thus could be of major importance in deciding which system farmers choose.

## Pesticides and Pest Management

### Herbicides--

Conservation tillage relies more on herbicides and less on cultivation to control weeds than conventional tillage. With no-till systems the reliance on herbicides is most marked, and in some circumstances may be complete. Other forms of conservation tillage may include some cultivation, but most usually require more herbicides per acre for weed control than conventional tillage. The amount more, however, is highly variable, judging from the literature. One report concerned with tillage in Illinois states that the chisel-plow system may require "slightly higher" amounts of herbicides per acre than the conventional system and that for no-till systems "higher herbicide rates or more costly herbicide combinations are usually needed for adequate weed control" (University of Illinois, June, 1979, pp. 6-7). Taylor, Reneau and Trimble show identical herbicide costs ($3.50 per acre) for conventional and "limited" tillage systems to produce furrow-irrigated winter wheat at Bushland, Texas. With no-till, however, herbicide costs are almost 350 percent higher ($15.65 per acre). For dryland grain sorghum in the Rio Grande Valley they show herbicide and application costs per acre of $6.63 for both conventional and "limited" tillage, but with no-till these costs are $23.38 per acre, 253 percent higher. Doster and Phillips, writing about corn production in central Indiana, also show identical costs for herbicides with conventional tillage and three kinds of conservation tillage, including coulter disc no-till. They indicate, however, that with "true" no-till herbicide costs would be 50 percent higher. Walker indicates that with conservation tillage herbicide costs in a corn-corn-soybean three-year rotation would be $40.28 per acre while with conventional tillage herbicide paraquat

costs in the same rotation would be $29.60 per acre. Most of the difference is because conservation tillage requires paraquat and conventional tillage does not. However, conservation tillage also requires more of given herbicides, according to Walker. Ameniya asserts that "reduced-till" may double the requirement for herbicides compared with conventional tillage.

R. E. Phillips et al. state that a reduction in tillage generally requires an increase in the use of "pesticides," and that no-till corn requires about 50 percent more "pesticides" than conventionally tilled corn. It is not clear in Phillips et al. whether "pesticides includes insecticides and fungicides as well as herbicides. However, Grant Thomas, one of the authors of Phillips et al., states that paraquat and atrazine, both herbicides, and a systemic insecticide such as furadan are included (personal communication).

There are a number of reasons why any form of conservation tillage may require more herbicides than conventional tillage, and why no-till definitely does. One might be called the substitution effect. Under specific conditions a given level of weed control may be achieved either by tillage or by herbicides, or by some combination of them. If control by tillage is reduced then a compensatory increase in the amount of herbicides applied is necessary to maintain the same level of control.

A second reason why conservation tillage likely will require more herbicides is the efficiency effect. Apart from the substitution effect, more herbicide must be applied to achieve a given level of weed control because some of the herbicide gets tied up by the crop residue which is a necessary concomitant of conservation tillage. Thus the efficiency of herbicide use is reduced. (Siemens and Oschwald, citing Erbach and Lovely; Fenster; Griffith, Mannering and Moldenhauer; University of Illinois; Robert Pope and Joseph Downs, University of Illinois, in discussion with the author).

Yet a third reason why conservation tillage may require more herbicides than conventional tillage is what might be called the environmental effect. The surface residue which accompanies conservation tillage usually reduces evaporation of water, so that typically soils are more moist with conservation tillage than with conventional tillage. The increased moisture improves the conditions for germination and growth of weeds (Griffith, Mannering and Moldenhauer; Pope and Downs in conversation with the author).

The substitution, efficiency and environmental effects are independent of one another, so their contributions to increased herbicides requirements with conservation tillage are additive. The literature does not indicate that all three effects are present in all cases of conservation tillage, and in fact there may be some circumstances, e.g. where weed problems are not serious in any case, where none of the three effects is important. In the usual case, however, it appears that one or more of the effects comes into play to increase herbicide requirements for conservation tillage relative to conventional tillage.

It frequently is stated in the literature that conservation tillage requires a greater variety of herbicides than conventional tillage, but it is not obvious that greater variety implies greater quantity. There also seems to be a consensus that over time perennial weeds become more important with conservation tillage, especially no-till. The reason is that herbicides do not attack the root systems of these weeds as tillage does, thus giving them a competitive advantage relative to annual weeds. It is not clear that the relative shift from annual to perennial weeds requires heavier applications of herbicides. It may mean instead that conservation tillage becomes uneconomic relative to conventional tillage in places where perennial weeds are a problem because some of these weeds cannot be adequately controlled with any amount of currently available herbicides. Johnson grass and Bermuda grass in particular are in this category. (Unger, Wiese and Allen; McWhorter and Jordan; Reicosky et al.; Harrold, Triplett and Edwards; Pope and Downs in conversation with the author). In such instances the economic disadvantage of conservation tillage results from unfavorable yields, not from the need for heavier applications of herbicides.

### Insect and Disease Control--

Although weed control is the main pest problem which sets conservation tillage apart from conventional tillage, insect and disease problems also may be more severe with conservation tillage. Where they are, conservation tillage may require heavier applications of insecticides and fungicides to achieve a given amount of insect and disease control. Insect and disease problems are more likely with conservation tillage because the crop residue left on the soil surface provide a favorable habitat for various insects and diseases.[9] Since no-tillage leaves the maximum amount of surface residue, insect and disease problems typically are more severe with no-till systems than with other kinds of conservation tillage.

Cotton--The likelihood and severity of these problems with conservation tillage also varies with the crop grown. Of the crops of interest in this study -- feed grains, wheat, soybeans and cotton -- cotton and corn have the most severe insect problems, judging from amounts of insecticides applied and percentage of acres treated.[10] In a review of the literature dealing with conservation tillage in cotton McWhorter and Jordan give no indication that the severity of insect problems in cotton is a function of the tillage system used. Their only comment with respect to diseases is that "...there has been limited research on diseases in cotton grown without tillage" (McWhorter and Jordan, p. 5).

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[9] The literature overwhelmingly supports this statement. However, R. E. Phillips et al. argue that the statement is not valid in all cases of conservation tillage. They assert that in some cases no-till appears to reduce certain diseases, and they mention Take-All in wheat. They also argue that even though the presence of crop debris may improve the habitat for certain insects and diseases, the associated conservation of moisture and reduction in soil compaction contribute to production of healthier plants better able to resist disease and insect pressure. They cite reduced damage from stalk rot in conservation tilled corn and sorghum as evidence.

[10] In 1976 58 percent of all insecticides applied to the crops of interest were applied to cotton. Twenty-nine percent were applied to corn. Sixty percent of land in cotton received at least one treatment with insecticide and 38 percent of corn land was treated. None of the other crops approached these two in amount of insecticide applied. Twenty-seven percent of land in sorghum received at least one insecticide treatment. For all the other crops of interest the percentage of land treated was much less than 27 percent. (Eichers, Andrilenas and Anderson).

Corn--Since corn probably is the crop most commonly grown under conservation tillage and is also a major user of insecticides, it is not surprising that the literature devotes more attention to corn than to any other crop in discussing the relationship of insect management to tillage systems. In a study by the USDA (May 1975) it is argued that the spread of conservation tillage could lead to a significant increase in the acreage of corn requiring at least one insecticide application. The reason, although the expression is not used, is the substitution effect, i.e. insecticides substitute for the plowing under of crop residue as a measure of insect control. There also is some suggestion in the literature of an efficiency effect resulting in heavier applications of insecticides to achieve a given amount of insect control. The reason is that the surface residue may interfere with efficient placement of insecticides in or on the soil (Fenster; Musick and Petty).

The University of Illinois, in the study previously referred to several times, produced a table bearing directly on the relationship between tillage system and insect management (See Table 7). The corn rootworm is by far the most important insect pest of corn throughout the Cornbelt and is the target of much the greater part of the insecticides applied to corn.[11] It is significant, therefore, that, according to Table 7, "reduced tillage," relative to conventional tillage, may increase corn rootworm populations or the potential damage by this insect, and no-till definitely will. This is consistent with the argument that because of the substitution effect conservation tillage would require heavier applications of insecticides than conventional tillage to control the corn rootworm. According to Ruesink, however (see footnote 11), experimental data do not support this inference.

Table 7 suggests that a number of other insect pests of corn also may be more troublesome with conservation tillage than with conventional tillage. Ruesink mentioned the Black Cutworm and the European Cornborer in particular among these pests. These and other insect pests have been discussed also by other writers as potentially more damaging with conservation tillage than with conventional tillage. (Triplett and Van Doren, Jan. 1977; Harrold, Triplett, and Edwards; Siemens and Oschwald; Reicosky et al.; Musick and Petty).

The plowing under of crop residues has long been a major element in disease control practices, in corn and in other crops as well (University of Illinois). With conservation tillage this practice is lost, or at least greatly reduced in effectiveness. Boosalis and Cook, in a review of the relationship of corn diseases to tillage system. argued that the surface residues left by conservation tillage foster root diseases as well as fungus

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[11] William Ruesink, entomologist at the University of Illinois, in conversation with the author, September 20, 1979.

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## TABLE 7. ESTIMATES OF THE EFFECT OF DIFFERENT TILLAGE PRACTICES ON INSECT POPULATIONS IN CORN[a]

| Pest | Spring plowing | Fall plowing | Reduced tillage | No-till[b] | Effective chemical control |
|---|---|---|---|---|---|
| Seed-corn beetles | 0 | 0 | ? | + | Yes |
| Seed-corn maggots | 0 | 0 | ? | + | Yes |
| Wireworm | 0 | - | ? | +(Sod) | Yes |
| White grubs | 0 | - | ? | +(Sod) | No |
| Corn root aphids | - | - | ? | +(Sod) | ? |
| Corn rootworm | - ? | - ? | +? | +(Corn) | Yes |
| Balck cutworms | ? | ? | ? | + | Yes |
| Billbugs | - | - | - | +(Sod) | Yes |
| European corn borer | - | - | + | + | Yes |
| True armyworms | - | - | - | +(Sod) | Yes |
| Common stalk borer | - | - | - | + | No |
| Slugs | - | - | - | + | No |
| Mice | - | - | - | +(Sod) | Yes |

[a] + = The practice will increase the population or the potential for damage by the pest.
- = It will reduce the population or potential for damage.
0 = No effect on the pest.
? = Effect unknown on the pest.

[b] The preceding crop will have a direct influence on the pest problem(s) in no-till corn.

Source: The University of Illinois, June 1979. Tillage Systems for Illinois.

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and bacterial blights. Consequently conservation tillage, particularly if practiced with continuous corn, may in time cause the build-up of a high enough level of disease inoculum to initiate severe disease outbreaks. Their studies show that corn plant residue may be an important primary source of the pathogen for northern leaf blight of corn in Nebraska. And they report that research on the Cornbelt in 1970 and 1971 indicated that the incitant of southern corn leaf blight depends on surface corn residue for survival through the winter. In a field partially conservation-tilled and partially conventionally-tilled to bury the residue, southern corn blight was much more severe on the conservation-tilled part of the field. In summarizing this evidence Boosalis and Cook state that there is "no doubt" that surface residues provide the initial inoculum that leads to the spread of southern corn blight in "many of the corn producing areas in the United States..." (p. 116). They cite other evidence indicating that the incidence of corn stalk rot also is higher with conservation tillage than with conventional tillage.

Jacobsen, Shurtleff and White, writing about diseases of corn in Illinois, also indict residues of the previous crop as a major factor in fostering these diseases. The greater threat of disease with conservation-tilled corn does not seem to imply, however, that corn grown with this system requires heavier application of fungicides or nematocides than conventionally-tilled corn. In fact, Boosalis and Cook assert that both northern and southern corn leaf blight are effectively controlled by use of resistant hybrids of corn.

In a review of alternative control measures for sixteen different kinds of corn disease, the University of Illinois gave first place to fungicides in only one instance, namely for control of corn seed rot and seedling blight. By far the most important control method was use of resistant or tolerant corn hybrids. For ten of the sixteen diseases this method was judged highly effective and for four of the remaining six diseases it was judged moderately effective. Jacobsen, Shurtleff and White, whose work is incorporated in the University of Illinois report, assert that use of resistant varieties also is the most economical means of controlling diseases of corn, in addition to being most effective.

This suggests that so far as disease control is concerned, conservation tillage of corn would not significantly increase the amount of fungicides applied relative to conventional tillage. However, the potential for increased disease damage with conservation tillage still could increase the cost of conservation tillage relative to conventional tillage if disease-resistant hybrid seeds cost more than other hybrids and conservation tillage farmers make greater use of the disease-resistant hybrids than conventional tillage farmers. We have been unable to pursue this issue in this study.

Soybeans--Compared to cotton and corn, soybeans and wheat are not much bothered by insects, although for soybeans the threat of insect damage is greater in the Southeast region than in the Cornbelt.[12] According to

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[12] In 1976 only 7 percent of land in soybeans and 14 percent of that in wheat was treated with insecticides.

William Ruesink (See footnote 11) insect pests of soybeans constitute a sporadic rather than a chronic threat, but the number of insects in the "sporadic" category could increase with conservation tillage because of the more favorable habitat it provides. The relative immunity of soybeans from the threat of serious insect damage is due primarily to the fact that the soybean is not indigenous to the United States. Ruesink states that he would not be surprised if in twenty years soybeans in the United States were to come under serious threat from insects, but so far there is no sign of this. For purposes of this report the significant finding is that for soybeans there is no significant difference between conservation tillage and conventional tillage with respect to potential insect damage.

The University of Illinois evaluated control measures for eleven diseases attacking soybeans. Presumably these diseases, being favored by the presence of crop residue, would be more threatening with conservation tillage than with conventional tillage. As in the case of corn, however, the most economical and effective control method for soybean diseases, according to the University of Illinois (also Jacobsen and Shurtleff), is use of resistant or tolerant seed varieties. For only two diseases are fungicides considered highly effective for control, and for one of these resistant varieties are rated equally or even more effective. There appears no reason to believe, therefore, that conservation tillage of soybeans would require significantly more fungicides than conventional tillage.

Wheat--A number of wheat diseases also are fostered by the surface residue left by conservation tillage (Boosalis and Cook; USDA, July 1977; University of Illinois; Jacobsen, Shurtleff and Knowland). However, in an evaluation of control methods for fourteen diseases of wheat in Illinois, the University of Illinois ranked use of resistant varieties as equal or preferable to fungicides in eight instances. For three diseases fungicides ranked ahead of resistant varieties. As in the cases of corn and soybeans, it does not appear that conservation tillage of wheat would require significantly more fungicides than conventionally-tilled wheat.

## Management

Most of the literature does not deal with the management requirements of conservation tillage relative to those for conventional tillage. Wherever management is discussed, however, the argument almost invariably is that conservation tillage is more demanding of management skills than conventional tillage.[13] A number of reasons typically are given: fewer passes over the field mean fewer opportunities to correct previous mistakes in plowing and planting; the surface residue makes it more difficult to get good seed placement, requiring extra care in this crucial operation; weed, insect and disease problems likely will be more complex, requiring more knowledge of the properties of a wider variety of pesticides and of how to apply them to get adequate pest control, or of crop rotation sequences and disease and insect resistant varieties as substitutes for pesticides; a greater variety of machinery and equipment may be needed with conservation tillage, increasing the need for knowledge of the right combination for the particular circumstances and perhaps also making more demands for machinery and equipment maintenance (University of Illinois, Triplett and Van Doren, Jan. 1977; Griffith, Mannering, and Moldenhauer; R. E. Phillips et al.; *No-Till Farmer*, April 1979 and Feb. 1980; Robert Pope, Joseph Downs and Malcolm Shurtleff in conversation with the author, September 20, 1979).

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[13] The only exception we have found is in an article by Carter and Colwick where it is asserted, with respect to cotton, that management is simplified with conservation tillage because the reduction in times over the field makes "appropriate timing and integration of operations" less important. As noted in the text, most other writers cite the reduction in number of times over the field as a major reason why management requirements are increased with conservation tillage.

There is a clear consensus that conservation tillage requires "more" management than conventional tillage, but it is not so clear what this means for the costs of production of the two systems. Evidently the meaning is not the same as the finding that conservation tillage requires more herbicides than conventional tillage. For given kinds and prices of herbicides, the requirement for more of them unequivocally increases the cost of conservation tillage relative to conventional tillage. Whether the requirement for "more" management has this effect depends on what it costs farmers to acquire the additional management skills. These costs would be of three shorts: (1) out-of-pocket expenses, e.g. for subscriptions to farm management publications, tuition for a short course in conservation tillage practices; (2) time spent in reading the publications, attending the course, and talking with neighbors, extension agents, soil conservation technicians and vendors of conservation tillage technology; (3) the difference between the net income the farmer would earn if he stayed with conventional tillage and what he would earn from conservation tillage, i.e. the costs of learning-by-doing. The first kind of cost surely would be trivial, and so would the second in pecuniary terms, i.e. the income foregone by engaging in the activities listed under (2) likely would be small. The psychic costs of these activities could be high, however, if the farmer places a high value on his leisure. The pecuniary costs of learning-by-doing clearly could be significant, depending upon the specific circumstances the farmer faces and how quick he is in acquiring the necessary knowledge through processes (1) and (2).

The literature gives no clues concerning the magnitude of the various costs of acquiring the managerial skills required for successful use of conservation tillage. In estimating the future spread of conservation tillage these costs obviously must be considered, but in our judgment they are not likely to be of major importance. The history of American agriculture, especially since the end of World War II, demonstrates that American farmers can quickly learn to use new, complex technologies when it is in their economic interest to do so. The extraordinary increases in this period in the use of fertilizers, pesticides, larger and more complex machinery, new seed varieties, new practices with respect to row spacing, and so on all attest to this, as well as to the efficiency of the U.S. agricultural establishment in developing new technologies and spreading the knowledge of how to use them. Indeed, the rapid spread of conservation tillage since the mid-1960s is itself testimony to this capacity of farmers and the institutional structure which serves them. Accordingly, we do not believe that the costs of acquiring the managerial skills required by conservation tillage will significantly impede its spread over the longer term. Should conservation tillage not continue to expand, it likely will be for reasons other than increased costs of management.

## Summary on Quantities of Resources

We considered labor, machinery, fuel, fertilizers, pesticides and management. There is little reason to expect differences between conservation and conventional tillage with respect to other inputs.

The literature is unanimous that conservation tillage requires less labor than conventional tillage, but estimates of the amount of the difference vary widely. We take the mean difference to be roughly 100 percent, i.e. conventional tillage requires about twice as much labor as conservation tillage. The literature is not always clear on this, but we assume the difference refers to pre-harvest activities. Harvest labor requirements would be about the same for both tillage systems, so the difference between them in total labor requirements would be less than 100 percent.

Machinery requirements per acre are less with conservation tillage for a farmer who converts 100 percent to this system. In terms of annualized costs per acre the saving is on the order of $3 to $10, judging from the estimates in Table 5. Many farmers, however, likely will want to retain the option of conventional tillage, and for them machinery costs likely would be higher than for farmers who forego this option.

No-till saves 3-4 gallons of diesel fuel equivalent relative to conventional tillage. For other forms of conservation tillage the saving is 1-3 gallons.

The evidence in the literature on differences in fertilizer requirements between conservation and conventional tillage is hard to evaluate, and we judged it inadequate to reach a firm conclusion. For purposes of the demonstration below we assume no difference in fertilizer requirements.

Conservation tillage typically requires more herbicides per acre than conventional tillage. The biggest and most firmly established difference is between no-till and conventional tillage, but it is probable that other forms of conservation tillage also require more herbicides. Corn produced with conservation tillage probably requires somewhat more insecticides than conventionally tilled corn. For the other crops of interest -- cotton, wheat, soybeans and feed grains other than corn -- insecticide requirements appear to be about the same for both conservation tillage and conventional tillage. This apparently is true also of fungicides and nematocides.

Primarily because of the herbicide difference conservation tillage requires more total pesticides per acre than conventional tillage. The literature provides few clues, however, to the amount of the difference. For purposes of the demonstration given below, we take Walker as a guide.

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He estimates that in a three-year corn-corn-soybean rotation in Iowa, pesticide costs with a till-plant system are one-third greater than in the same rotation with conventional tillage.

Conservation tillage is more demanding of management skills than conventional tillage. However, we judge the costs of acquiring the necessary skills to be low and not an important obstacle to the spread of conservation tillage.

The literature provides no easy guide to translating the estimates of differences in quantities of some inputs into differences in total costs of conservation and conventional tillage. Some at least rough estimate of these cost differences is necessary, however, if we are to reach even tentative judgments about the economic attractiveness of conservation tillage relative to conventional tillage. We, therefore, have ventured to make such estimates. They are given in Table 8. The crudity of the estimates of costs for conservation tillage will be obvious to the reader who has followed the discussion to this point. We believe the ordinal relationship between the costs for conservation and conventional tillage is correct, but the specific differences clearly are subject to a wide range of error. The estimates for conventional tillage are systematically biased downward because they reflect land in both conventional and conservation tillage in 1979. However, the estimates of conservation tillage also are biased downward because they assume total labor costs are only half those of conventional tillage. In fact, it is only pre-harvest labor costs that differ by this much.

Walker, in a detailed analysis of costs of producing corn and soybeans in southwestern Iowa with conventional tillage and conservation tillage, found the following for a three-year corn-corn-soybean rotation:

Per acre costs (excluding land)

| Conventional tillage | | Conservation tillage |
|---|---|---|
| Spring-plow | Fall-plow | (till-plant) |
| $ 345 | $ 319 | $ 310 |

The fall-plow figure is lower than that for spring plow primarily because of lower machinery costs. Walker's investigation showed that with the fall-plow alternative timing of farm operations was less crucial than with spring plowing, permitting the farmer to operate with less powerful and, therefore, less expensive equipment. Comparable figures from Table 8 (two years of corn followed by one year of soybeans) are $435 for conventional tillage and $403 for conservation tillage. We would expect the Table 8 figures to be higher than Walker's since his price data were for 1975 and there was considerable inflation of farm input prices from 1975 to 1979. The difference between Walker's estimates of fall-plow costs and conservation tillage

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## TABLE 8. ESTIMATES OF COSTS PER ACRE FOR CONSERVATION TILLAGE AND CONVENTIONAL TILLAGE IN THE UNITED STATES IN 1979, SELECTED CROPS

| | Total Costs[a] | | Labor | | Machinery | | Fuel | | Pesticides | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Conv-till[b] | Cons-till | Conv-till[b] | Cons-till | Conv-till[b] | Cons-till | Conv-till[b] | Cons-till | Conv-till[b] | Cons-till |
| Cotton | $ 279 | $ 264 | $ 26.69 | $ 13.34 | $ 68.69 | $ 63.69 | $ 12.85 | $ 10.85 | $ 17.30 | $ 23.07 |
| Corn | 165 | 154 | 13.24 | 6.62 | 36.32 | 31.32 | 9.02 | 7.02 | 8.72 | 11.63 |
| Sorghum | 114 | 101 | 13.43 | 6.72 | 35.15 | 30.15 | 10.66 | 8.66 | 3.08 | 4.11 |
| Wheat | 79 | 68 | 9.25 | 4.63 | 25.30 | 20.30 | 5.57 | 3.57 | 1.21 | 1.61 |
| Soybeans | 105 | 95 | 12.21 | 6.10 | 31.28 | 26.28 | 6.83 | 4.83 | 9.13 | 12.17 |

[a] Exclusive of land.

[b] Estimates by the USDA of costs per acre in 1979, for the nation as a whole, for each crop. Thus the estimates reflect costs of conservation tillage as well as conventional tillage since about twenty-five percent of cropland was in conservation tillage in 1979 (see table 3).

Sources: Conventional tillage from USDA, June 15, 1979, pp. 41-42. Conservation tillage: labor costs assumed to be one-half those for conventional tillage; machinery costs (annualized) assumed to be $5 less; fuel requirement (diesel equivalent) assumed to be 2 gallons less at $1 per gallon; pesticide costs assumed to be one-third more (following Walker). All costs other than those listed are assumed to be the same for both tillage systems.

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costs is considerably less than our difference between conventional and conservation tillage costs. His difference between spring-plow costs and conservation tillage costs is much like our difference, however. We conclude that the estimates in Table 8 provide quite rough but serviceable indicators of the differences between conservation and conventional tillage with respect to total non-land costs of producing the crops listed.

If there were no differences in yields between the two tillage systems Table 8 would imply the rapid substitution of conservation tillage for conventional tillage. Indeed substitution would be expected even if conservation tillage yields were less than those for conventional tillage so long as the difference were not so great as to offset the cost advantage of conservation tillage. The "break-even" difference in yields, i.e., the difference at which farmers would have no incentive to switch to conservation tillage, would be that at which net revenues per acre (gross revenues minus costs, except land) were equal. Table 9 shows break-even yields, given average seasonal crop prices received by farmers in 1979 and the cost figures in Table 8. The table suggests that conservation tillage could deliver somewhat smaller yields than conventional tillage without suffering a competitive disadvantage. The margin is small, however. Moreover, the table reflects experience only in a single year, but yields vary from year to year. A farmer will compare not only average yields of the two tillage systems over a period of years; he also will consider whether the systems differ with respect to the year-to-year variability of yields. Obviously the analysis of the economics of conservation tillage relative to conventional tillage must consider the yield performance of the two systems in some depth.

TABLE 9. BREAK-EVEN YIELDS FOR CONSERVATION TILLAGE AND ACTUAL YIELDS IN 1979, SELECTED CROPS

| | Bushels/acre | | | | lbs./acre |
|---|---|---|---|---|---|
| | Corn | Sorghum | Wheat | Soybeans | Cotton |
| Actual yields | 109.4 | 62.9 | 34.2 | 32.2 | 551 |
| Break-even yields | 105.0 | 59.9 | 31.4 | 30.5 | 526 |
| Break-even as % of actual | 96.0 | 95.2 | 91.8 | 94.7 | 95.5 |

Sources: Actual yields -- all except cotton from USDA (April 1980). Cotton from USDA (Mar. 1980).
Break-even yields -- yields which would equalize net revenues per acre (gross revenues per acre minus total costs, except land) for conservation tillage and conventional tillage.
Prices - USDA (June 1980). Season averages received by farmers.
Costs -- Table 8.

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## YIELDS

### Long-term Yields

It is important to distinguish between the short-term (one or two years) and long-term (decades) yield effects of tillage technologies. Over the long term the lower rates of erosion associated with conservation tillage can give it a decisive yield advantage relative to conventional tillage. Whether this occurs depends upon (1) the differential advantage of conservation tillage in reducing erosion; (2) the amount of topsoil and the nature of the underlying parent material; (3) the relation of changes in the amount of topsoil to changes in yield over time.

Depending upon these three conditions, the effect of the erosion factor in the choice of tillage technologies is either neutral or it favors conservation tillage. It can never favor conventional tillage. Consequently, where conservation tillage confers a short-term yield advantage farmers will always choose that technology (given its cost advantage depicted in the previous section). Even where short-term yields of conservation tillage are less, however, farmers may yet choose that technology over conventional tillage if the erosion advantage of conservation tillage is sufficiently strong. The strength of the advantage depends upon (1) the annual differences in yields between conservation and conventional tillage as determined by the three factors listed above; (2) the cost to the farmer of substituting fertilizers or other inputs for the lost soil, thus offsetting the erosion induced decline in yields; (3) the length of time over which the yield differences matter to the farmer; (4) the farmer's expectations about future crop prices relative to current crop prices; (5) the rate of discount the farmer applies to future earnings.

The role of these factors in the farmer's choice between conservation tillage and conventional tillage can be usefully discussed by reference to Figure 1.[14] Assuming for the moment that crop prices are constant over time, conventional tillage has a clear yield advantage over conservation tillage between time $t$ (the "present") and $t + n$ despite the fact that conventional tillage yields decline because of erosion. If the farmer's time horizon extends only to $t + n$, he will choose conventional tillage despite its erosion disadvantage.

From $t + n$ to $t + 2n$ conservation tillage has the yield advantage, the undiscounted cumulative value of which (assuming constant crop prices) is exactly equal to the advantage of conventional tillage between $t$ and $t + n$ (triangle abc = triangle cde). However, even if the farmer's decision horizon extends to $t + 2n$ he still will choose conventional tillage so long as he applies any positive rate of discount (no matter how small) to future earnings. This is because any rate of discount will make the present value of the cumulated yield advantage of conservation tillage between $t + n$ and

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[14] For simplicity of exposition we assume in Figure 1 that the effects on yields of subsituting fertilizer or other inputs for the soil lost to erosion are incorporated in the yield curve for conventional tillage.

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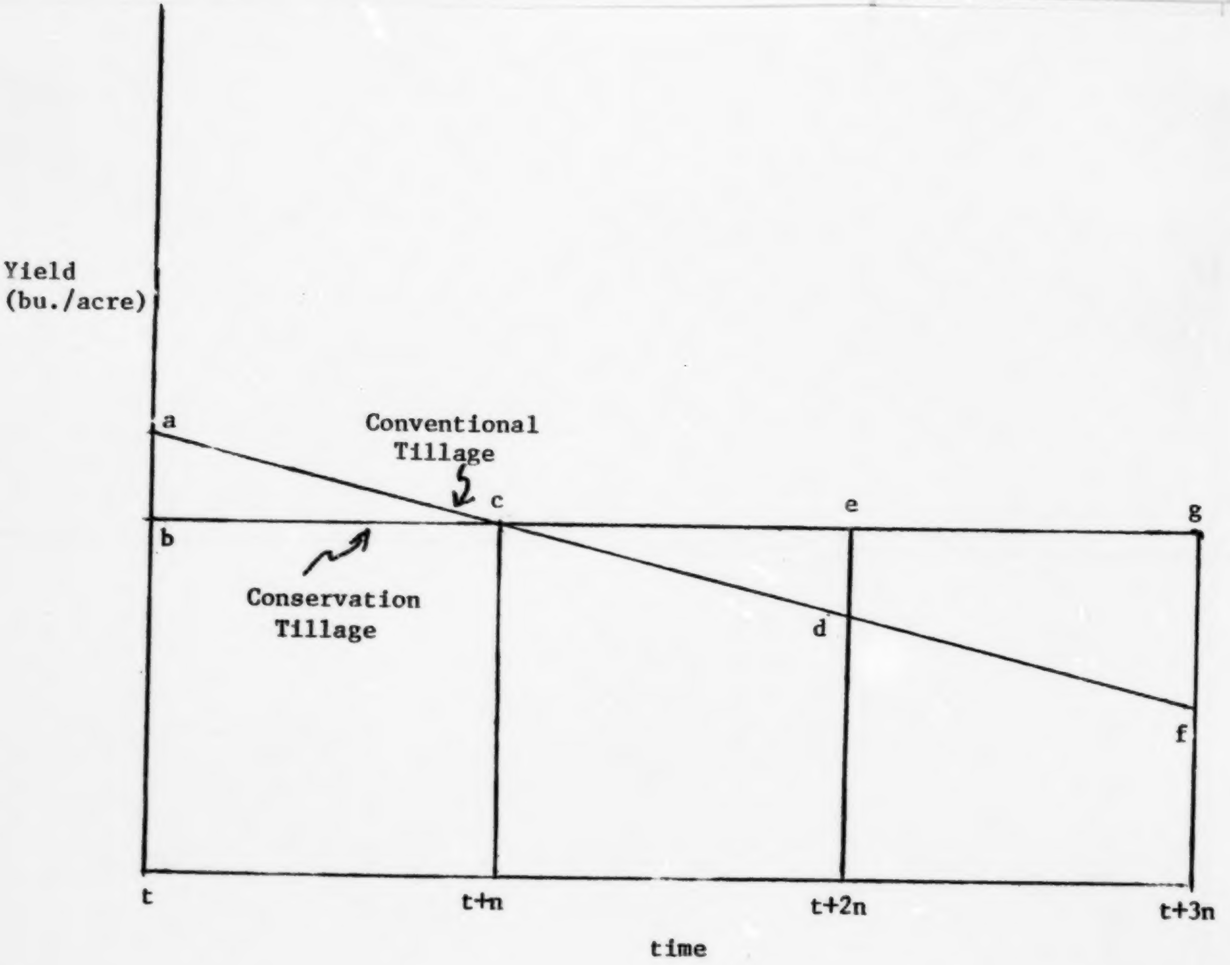

Figure 1. Long-term yield relationships: conservation tillage and conventional tillage.

t + 2n less than the present value of the cumulated yield advantage of conventional tillage between t and t + n.

If the farmer's time horizon extends to t + 3n, conservation tillage clearly has the yield advantage before discounting (given constant crop prices over the entire peirod). Whether the advantage remains after discounting depends upon the rate of discount. The higher the rate the more the triangle cfg shrinks relative to the triangle abc. At some rate cfg would just equal abc and the farmer would be indifferent as between conservation tillage and conventional tillage despite the long-term decline in yields resulting from conventional tillage.

We have assumed constant crop prices over time. However, if the farmer thinks future prices will be higher than current prices the yield advantage of conservation tillage will be larger, i.e., a rise in expected prices will increase the triangle cfg relative to abc. Of course if future prices are expected to be lower relative to current prices cfg will shrink relative to abc.

In Figure 1 we have assumed for simplicity that yields with conventional tillage decline linearly because of erosion. In fact, the curve of yield decline can take other shapes, depending upon the amount of top soil, the net annual rate at which it is eroded, and the nature of the parent material. On deep soils yields may decline little if any for some years and then fall linearly or at increasing rates. Because of discounting, the long-term yield advantage of conservation tillage will be less on such soils than on soils where the yield decline is linear, even if the cumulative (undiscounted) decline is equal on both soils.

The discussion also has assumed implicitly that there are no offsetting factors to counter the yield decline caused by erosion. In fact, increased application of fertilizer or other technological improvements can and do counteract the yield effects of erosion, although at some cost to the farmer. There are limits to this, so long as some amount of topsoil is necessary for plant growth, but the limits may not be encountered within the farmer's time horizon. The effect, of course, is to weaken the long-term yield advantage of conservation tillage relative to conventional tillage.

It often is argued that farmers who rent or lease their land from others will have a shorter planning horizon than owner-operators and will, therefore, be less sensitive to the long-term yield effects of erosion. A recent study by Lee, however, casts doubt on this hypothesis. The study did not directly examine differences among tenure groups with respect to attitudes toward erosion, but it showed no significant differences among groups in per-acre amounts of erosion.

In thinking about farmers' choices between conventional tillage and conservation tillage it obviously is important to know something about the difference between the two technologies with respect to erosion, the long-term effects of erosion on yields, the number of years over which these differential yield effects enter the farmer's calculations, his ability to offset erosion-induced yield declines through technology, his expectations

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about future crop prices relative to current prices, and his rate of discount. The literature indicates a consensus that conservation tillage reduces erosion by 50 to 90 percent relative to conventional tillage (more about this below in the section on environmental impacts), but we know relatively little about the other factors mentioned. However, a study by Seitz et al. indicated that under 1974 price and technological conditions corn-soybean farmers in a typical Cornbelt watershed would be insensitive to the long-term yield effects of erosion unless their planning horizon was forty years and they did not discount. If they discount at a rate as low as 5 percent, their planning horizon would have to be sixty years. It seems unlikely that many farmers have such distant planning horizons.

In its work under the Soil and Water Resources Conservation Act (RCA) the USDA (1980) made rough estimates of the effects of erosion on yields on various soils all around the country. The USDA is continuing work to refine these estimates, and in time we should have reasonably good information about erosion-yield relationships over time. This information no doubt will be passed on to farmers by SCS and Agricultural Extension personnel, and should begin to enter into farmers' thinking about conservation tillage to a greater extent than at present. We still know little, however, about the length of the farmer's time horizon, his expectations about future crop prices or his rate of discount. There is much speculation about these factors in the literature, but not enough hard facts to warrant firm generalizations about effects on farmers' choices between conservation tillage and conventional tillage.

In the end, the only confident statement we can make is one already made above: since conservation tillage never produces more erosion than conventional tillage and typically produces much less, the erosion effect on yields can never be to the disadvantage of conservation tillage. At worst it will be neutral, and it must often be positive, although without much additional research we cannot identify the specific situations in which this would be true or estimate the strength of the advantage.

## Short-term Yields

The question of the long-term yield effects of erosion would be moot if conservation tillage had a clear short-term yield advantage over conventional tillage. The vast majority of the literature in fact deals with short-term yield differences and shows no clear pattern of advantage for either technology. Some studies show yields higher for conservation tillage, others show them lower and still others show no significant differences. The specific circumstances of soil, weather, and kind and quantity of weeds are of crucial importance in determining relative yield response, and these conditions differ widely, both spatially and even temporally in the same location. Other factors less often mentioned, and apparently less important, are seed placement and soil compaction. Because of the surface residue and relatively little soil disturbance with conservation tillage it sometimes is difficult to get good seed placement, putting the seeds at uniform depths and in firm contact with the soil. When this happens yields may suffer.

Soil compaction restricts the penetration of air and water in the soil and impedes root growth, with adverse effects on yields. The literature gives conflicting accounts of the effects of tillage technologies on soil compaction, perhaps because the problem has been little studied.[15] One line of argument is that conservation tillage eases the problem of soil compaction because it requires fewer trips across the field and uses lighter equipment. Phillips and Young represent this position, saying the "soil conservationists who have been observing no-tillage fields for years report a noticeable reduction in compaction. Fields of clay soils in continuous row-crop production for nearly a decade show that early fears of compaction due to prolonged no-tillage culture now may be dismissed" (p. 57). In its survey of conservation tillage the USDA (May, 1975) also credits the technology with a yield advantage because of reduced soil compaction.

A contrary line of argument, however, is that the reduction or elimination of tillage reduces the porosity of the soil, i.e. increases compaction. Griffith, Mannering, and Moldenhauer, for example, cite studies in Indiana showing that soil density after planting greatly increased with no-till production of corn compared with conventional tillage. Density was slightly higher with the till-plant system and slightly lower with the chisel system. The writers go on to state that "Obviously, a higher soil density offsets some positive effects of conservation tillage on soil structure" (p. 25). However, the studies they cite suggest that if compaction is a problem with conservation tillage systems it is confined to no-till.

Soil Moisture and Temperature--

If there are differences about the effects of conservation and conventional tillage on soil compaction, there appear to be few about the effects on soil moisture and temperature. There is in fact a strong consensus that in the plant root zone soil moisture generally is higher with conservation tillage and that in the spring soil temperatures are lower. Both of these conditions have a bearing on yields of conservation tillage relative to conventional tillage. In areas where rainfall is the principal factor limiting plant growth, as in part of the Northern Plains, the moisture-conserving feature of conservation tillage is a distinct plus. Indeed, this appears to be the principal reason for the relatively widespread use of conservation tillage in that area (See Table 3). The moisture-retaining characteristic of conservation tillage, however, is an advantage in any area subject to periods of drought or where soils are droughty. The characteristic is a distinct disadvantage, however, on poorly drained soils.[16]

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[15] Unger, Gerard and Wendt state that data on the effects of conservation tillage on soil compaction are limited.

[16] The literature is virtually unanimous on this point. The only unqualified exception I have found is in Phillips and Young who, with respect to poorly drained soils assert that "Any problem soils which produce satisfactory crops by conventional methods can produce comparable no-tillage crops with the same level of careful management" (p. 175). A qualified exception is in Triplett and Van Doren (April 1977), who report that yields of continuous corn are lower on poorly drained soils with conservation tillage, but that the disadvantage disappears if corn follows some other crop.

Cosper, implicitly assuming that yield response is crucial in determining the competitiveness of conservation tillage relative to conventional tillage, finds the key to yield response in soil characteristics, with moisture retention capacity most important. More specifically, he asserts that "Those physical features most significant in designating an acceptable tillage system include inherent drainage and soil wetness levels, structural stability, water percolation and surface soil texture. Among these properties, soil wetness is perhaps the most restrictive in limiting the range of usable tillage systems" (p. 17, emphasis added). Cosper uses these soil characteristics, especially wetness, to develop estimates of the maximum amount of land that could be economically put in conservation tillage in Ohio, Indiana, Illinois, and Iowa. As of this writing (August 1980) he is preparing similar estimates for the Northern Plains region.

Cosper's judgment that soil drainage is a key element in yield differences between conservation tillage and conventional tillage is widely shared in the literature. The evidence is strong that on poorly drained soils yields with conservation tillage are lower than those with conventional tillage. While the reasons for this appear not to be completely understood, a number are given in the literature. Triplett and Van Doren (Jan. 1977, p. 33) "suspect that disease organisms build up in poorly drained soil if the soil is not plowed." Subsequent research on this problem in Ohio in fact implicated a disease organism of corn as a cause of reduced corn yields on certain poorly drained soils.[17] The research dealt with clayey soils with a high "shrink-swell capacity." When these soils dry they crack and corn roots follow the cracks. Subsequent heavy rains fill the cracks, and because of poor drainage the water remains long enough to provide a favorable environment for a water-loving disease organism which attacks the corn roots. The problem can be avoided, or at least diminished, if corn is rotated with soybeans because the disease organism cannot survive on soybean roots. Alternating plowing with no-till also will reduce the problem because plowing breaks up the soil and destroys the offending cracks. (Note, however, that this solution to the problem would require the farmer to maintain the equipment necessary for both conventional and conservation tillage. Also over a period of years it would reduce the average amount of land in conservation tillage annually).

Based on their research in Ohio, Triplett, Van Doren, and Bone also found that on poorly drained soils excessive moisture in the spring may cause corn seeds to decay before the seedlings have a chance to emerge.

Pope, Downs, and Shurtleff of the University of Illinois also have argued that excessive wetness on poorly drained soils can promote disease organisms which adversely affect yields.[18] Wetness also fosters the growth

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[17] The following account is based on a discussion between the author and Glover Triplett, Ohio Agricultural Research and Development Center, on July 22, 1980.

[18] In discussion with the author on September 20, 1979.

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of weeds. They note further that wetness may delay planting and, in Illinois at least, this can reduce yields because in that state, the favored varieties of corn and soybeans require the full season to give their best performance.

Soil temperature generally is lower with conservation tillage than with conventional tillage, especially in the spring, because the crop residue reflects some of the sun's heat. On poorly drained soils temperatures may also be lower with conservation tillage because of the greater moisture content of these soils and the high heat capacity of water.

If soil temperatures are too low, the availability and uptake of nutrients, particularly P and N, will be inhibited, slowing seed germination, seedling emergence, and subsequent early growth (Willis and Amemiya). Optimum soil temperatures vary among crops and, for some crops at least, over the crop growth cycle. Willis and Ameniya report that the optimum root temperature for beans is about 80°F for young plants, but lower than that for older plants. For corn the optimum is about 76°F. However, the temperature-ultimate yield relationship for corn evidently is not linear according to Willis and Ameniya. They cite research indicating that where average soil temperature at a depth of 4 inches was higher than 75°F during the first 6 to 8 weeks after planting, corn yields with conservation tillage were comparable to those with conventional tillage.

The delay in seed germination, emergence and early growth resulting from low soil temperatures does not necessarily mean lower future yields. It may, however, if the seedlings still are relatively undeveloped and vulnerable when populations of disease organisms and insects begin to expand. The delay in early growth also is a disadvantage where crops require a "full season," as in the case of corn and soybeans in Illinois, noted above. Indeed, R. E. Phillips et al. assert that the delay in spring planting required by lower soil temperatures is a disadvantage to conservation tillage throughout the central and northern United States. Ameniya (p. 33) also asserts that the low soil temperature associated with conservation tillage is a "serious obstable to adoption" of the technology in the northern Cornbelt.

Weeds--

Apart from soil wetness and low soil temperature the major factor adversely affecting yields with conservation tillage is weed control. Indeed, Pope, Downs, and Shurtleff assert that in Illinois the problem of weed control is the principal obstacle to the further spread of conservation tillage.[19] Other writers state that for the eastern Cornbelt "...weed control is still the major obstacle to expansion of conservation tillage on well-drained soils"

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[19] This is consistent with Cosper's findings with respect to the relation of soil drainage characteristics to the potential spread of conservation tillage. He finds that in Illinois 69 percent of the tillage acres could be in some form of conservation tillage. However, in 1978 much less than 69 percent of this land was conservation-tilled, indicating that something other than soil characteristics was the limiting factor. The observation of Pope, Downs, and Shurtleff suggests it may have been weeds.

(Griffith, Mannering, and Moldenhauer, p. 26). Reichert (p. 5) cites James E. Box, Jr., director of the Southern Piedmont Conservation Research Center of the USDA in Watkinsville, Georgia to the effect that no-till has been most successful where weed problems are least. Box gives this as a reason why no-till has spread less rapidly in southern Georgia than in some states further north. Unger, Wiese, and Allen say that in the southern Great Plains moisture is so limited that weed control during fallow and when the land is in crops must be nearly perfect or yields will be low. Achieving the necessary degree of weed control with herbicides alone is difficult, and this has slowed acceptance of no-tillage systems. However, conservation tillage short of no-tillage has proved more practical.

We already have discussed the problem of weed control at some length in the section on cost differences between conservation and conventional tillage. The emphasis there was on the increased cost of herbicides required by conservation tillage to achieve yields comparable to those of conventional tillage. The emphasis here is on situations where no amount of herbicides will provide enough control to give comparable yields, or where the additional amount required would be so great as to be clearly uneconomic. Obviously the second situation is similar to that implicit in the discussion of herbicide costs. The difference is that here we have in mind situations where the additional amounts of herbicides required to achieve comparable yields would be so great as to make it immediately obvious to the farmer, without any "fine tuning" in his calculations, that conservation tillage would not be economical.

In the section on costs it was noted that perennial weeds typically become more important with uninterrupted use of conservation tillage. This theme is found throughout the literature on tillage technologies (e.g. Reichert; Davidson and Santelmann; Griffith, Mannering, and Moldenhauer; Randell and Swan; Ameniya; Wiese and Staniforth). A companion theme is that there are no fully effective herbicides for controlling certain perennial weeds (Pope, Downs, and Shurtleff, University of Illinois, in discussion with the author) and that conservation tillage will face severe difficulties or should not be used at all in areas infested with these weeds. Reicosky et al. cite research in Virginia which cautions against use of no-tillage in fields infested with Johnson grass, nutsedge, broomsedge, and Bermuda grass. They also cite research to the same effect in Kentucky where the problem weeds are Johnson grass, bullnettle, bindweed, and others. Griffith, Mannering, and Moldenhauer recommend that where perennial weeds "cannot be controlled chemically, moldboard plowing is recommended" (p. 26). Writing about conservation tillage in the Southern Plains Unger, Wiese, and Allen state that "Perennial weeds are difficult to control in most tillage systems and until recently there were no reduced-till systems that would work in areas infested with these weeds" (p. 47). They note, however, that glyphosate "more recently" has shown potential for controlling both perennial broadleaf and grassy weeds. Harris, Burnett, and Williams note that Johnson grass is a major problem in central and east Texas, particularly in cropping systems involving grain sorghum. In fact, achieving adequate control of Johnson grass, and other weeds, with conservation tillage in this region "...will be a difficult job with existing technology" (p. 10). Weaver, also writing about Texas but without reference to a particular region within the state, asserts that conservation tillage "...is not suggested in fields infested with perennial weeds such as Bermuda grass, Johnson grass, or nutsedge" (p. 77). McWhorter and Jordan write that "It is generally conceded that no-tillage should not be used in fields infested with perennials such as Johnson grass--or Bermuda grass..." (p. 7). With respect to cotton McWhorter and Jordan state that the presence of perennial weeds in the fields "...prevents use of no-tillage and restricts use of minimum-tillage production" (p. 15). They continue as follows:

> "Many farmers and researchers have attempted to use both no-tillage and reduced-tillage in cotton. Those that have been successful used fields that were relatively free of weeds. Thus it appears that weeds represent the major limiting factor in no-tillage and reduced-tillage production of cotton. Unfortunately, the severity of the overall weed control problem in cotton appears to be increasing. The continued spread of troublesome weeds will increase the importance of cultivation in cotton unless new technologies are developed for contorl of these pests" (p. 15).

Double-cropping--

Because conservation tillage permits the planting of a crop directly in the stubble of a preceding crop immediately after harvest it saves time and in effect extends the length of the growing season, making double-cropping possible in areas previously closed to this practice. Double-cropping, of course, increases the yield of the land, thus reducing average costs of land and other fixed inputs. In areas where conservation tillage permits double-cropping and conventional tillage does not, conservation tillage clearly has an advantage (if soils are well drained and weeds can be controlled by herbicides). Even where the growing season is long enough to permit double-cropping with conventional tillage, conservation tillage has an advantage because it retains more of the soil moisture needed by the second crop than conventional tillage does.

Pope, Downs, and Shurtleff (in discussion with the author) state that double-cropping of soybeans following wheat is common in the lower third of Illinois, and this probably defines roughly the northern limit of double-cropping in the region of the country east of the Rocky Mountains.[20] Hayes cites Lewis to the effect that below this limit the southeastern part of the country has the greatest potential for double-cropping with conservation tillage because of the longer growing season in that region.

In the Southeast and Cornbelt the typical double-cropping sequence is soybeans following fall-planted wheat or other small grain. Further west, in the Plains region, the more likely sequence is wheat-sorghum.

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[20] Griffith, Mannering, and Moldenhauer would put the limit a little further north, saying that most double-cropping in Ohio, Indiana, and Illinois is in the southern half of those states. Triplett (in correspondence with the author) asserts that the northern limit for double-cropping is north of Ohio.

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### Yield Variability--

Farmers who are risk averters will consider differences in the annual variability of yields between conservation tillage and conventional tillage as well as differences in average yields over a number of years. Such farmers will be more impressed by the probability of below-average yields than by the probability of yields above average; consequently the greater the expected variability of yields over time the higher the rate at which those yields will be discounted by risk-averse farmers. These farmers will prefer the technology with the lowest annual variation in yields even if average yields of the two technologies over time are identical, while risk-neutral farmers would be indifferent between the two technologies in this case.

We have found no studies which address the risk issue in precisely the terms just stated. However, Taylor, Reneau, and Trimble have considered the issue in somewhat different terms, asserting that risk-averse farmers, or those who take a "safety first" attitude, would prefer that technology which gives the highest net return (or lowest net loss) in the worst of several years. They examined cost, yield, and revenue data for conventional tillage, limited tillage, and no-tillage systems used over a three-year period in production of irrigated wheat at Bushland, Texas and dryland grain sorghum in the Rio Grande Valley. They found that for both crops average net returns over the three years were highest for no-till. No-till net returns also were highest in the best of the three years. However, no-till gave the lowest net returns or highest net losses in the worst year, indicating that "safety first" farmers would not choose no-till despite its best average and best year performance. The limited tillage system would be chosen for production of irrigated wheat (its net losses in the worst year were lowest) and conventional tillage would be chosen for production of grain sorghum (its net earnings in the worst year were highest). In all cases differences between worst year yields and average yields were the main reason for differences in net returns (or losses).

Taylor et al. do not discuss the reasons for the observed patterns of yield variability among the three tillage systems. Consequently their study provides no insights from which we might generalize about tillage-related variations in annual yields in other parts of the country. The study serves to demonstrate, however, that yields with conservation tillage and conventional tillage may differ in variability over time as well as on average, and to highlight the importance of variability as a separate factor in farmers' choices between the two technologies.

### Summary on Yields

Because conservation tillage never causes more erosion than conventional tillage and usually causes less, the long-term effect of erosion on yields can never be to the disadvantage of conservation tillage when farmers choose between the two technologies. On level land where erosion is not a problem, the erosion factor will be neutral as between the two technologies. Whether the erosion factor favors conservation tillage on more erosive soils depends upon the erosion-induced difference in annual yields between the two

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technologies; the cost to the farmer of offsetting the yield loss with conventional tillage by substituting fertilizer or other inputs for the soil lost to erosion; the length of time over which the yield differences make a difference to the farmer; crop prices expected by the farmer relative to current prices; and the rate of discount the farmer applies to future earnings. We know little about these factors except that they all will vary widely among farmers and some of them (e.g., price expectations) will vary over time for any given farmer. Consequently, it is impossible to make firmly grounded generalizations about the strength of the erosion factor in farmers' choices between conservation tillage and conventional tillage, except that it will never work against conservation tillage.

Given the uncertainty about the effect of long-term yield differences on farmers' choices between the two tillage technologies, it is likely that for most farmers the choice is most influenced by short-term differences. Here some firmly grounded generalizations appear warranted: actual experience, both experimental and in farmers' fields, indicates that yield differences between the two technologies vary widely from place to place and over time, with conservation tillage having the advantage in some instances and not in others. However, on well-drained soils where weeds can be controlled by herbicides about as well as with cultivation, conservation tillage yields are fully competitive with yields of conventional tillage. On droughty soils or in areas where rainfall is a limiting factor, conservation tillage typically will give higher yields than conventional tillage. Moreover, the time-saving and soil moisture retention characteristics of conservation tillage permit double-cropping in areas where it would not be economically feasible with conventional tillage. Finally, the two tillage systems may differ with respect to yield variability over time, and this could influence the choices between the technologies of farmers not indifferent to risk.

## SUMMARY ON ECONOMICS

In the section on quantities and costs of resources it was concluded that for corn, sorghum, wheat, soybeans, and cotton conservation tillage, under price and other conditions of 1979, had a cost advantage of roughly 5 to 10 percent relative to conventional tillage (see Table 9). It follows that in areas with well-drained soils, adequate control of weeds with herbicides, and potential for double-cropping the economics to the farmer would clearly favor conservation tillage. Two questions arise: (1) Is the present geographical distribution of conservation tillage consistent with this assertion? (2) Does the assertion provide any insights to the role of economics in the future spread of conservation tillage?

There is little information with which to address either of these questions. With respect to the first, however, Table 10 is relevant. Column (1) in the table is based on Cosper's analysis of soil types in the four states, with special attention to soil drainage characteristics. The column indicates that as one moves from the eastern to the western Cornbelt the percentage of tillable land with drainage characteristics favorable to conservation tillage increases. Column (2) indicates a similar progression in the

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percentage of land actually in conservation tillage. The two columns, therefore, are consistent with the hypothesis that soil drainage is a key factor in determining the yields and hence the economic feasibility of conservation tillage.

TABLE 10. PERCENTAGE OF LAND APT FOR CONSERVATION TILLAGE AND IN CONSERVATION TILLAGE, OHIO, INDIANA, ILLINOIS, AND IOWA

| | (1) Percent apt for Conservation tillage[a] | (2) Percent in conservation tillage, 1979[b] |
|---|---|---|
| Ohio | 47.5 | 8.0 |
| Indiana | 53.4 | 22.8 |
| Illinois | 65.9 | 28.0 |
| Iowa | 76.4 | 38.9 |

[a] From Harold Cosper (p. 26). Land is "tillable acres," and for each state is almost exactly the same as the sum of cropland and pasture as reported in the USDA's National Resources Inventory of 1977. Aptness for conservation tillage is based on soil characteristics, particularly with respect to drainage.

[b] From No-Till Farmer, March 1979.

As indicated above, Cosper is extending his analysis of soil types to the Northern Plains, but those estimates are not available as of this writing. Nor are there similar estimates for any other region of the country. Consequently, we are unable to judge whether the distribution of conservation tillage outside the Cornbelt is consistent with the hypothesis that soil drainage is a key factor.

There are other useful hypotheses, however, which can be examined. Because of the semiarid climate in the Northern Plains (North Dakota, South Dakota, Nebraska, and Kansas) one would expect the percentage of land in conservation tillage in the region to be relatively high. However, because conservation tillage lowers soil temperature in the spring, thus delaying planting relative to conventional tillage, the percentage of land in conservation tillage would be expected to decline as one moves with the diminishing growing season from Kansas to North Dakota. For the same reason one would expect the percentage of conservation-tilled land in the Lake States (Michigan, Wisconsin, and Minnesota) to be less than in the Cornbelt.

Because of the favorable prospects for double-cropping with conservation tillage in the Southeast (Lewis) the percentage of conservation-tilled land ought to be relatively high in that region, while it ought to be relatively low in the Mississippi Delta and the Southern Plains (Texas and Oklahoma) because of the problems of controlling weeds in those regions with herbicides, particularly perennial weeds in cotton.

Table 11 shows that the regional distribution of conservation tillage in 1979 was generally consistent with these expectations.

TABLE 11. PERCENT DISTRIBUTION OF LAND IN CONSERVATION TILLAGE, VARIOUS STATES AND REGIONS, 1979

| | Percent |
|---|---|
| Kansas | 50.1 |
| Nebraska | 47.1 |
| South Dakota | 34.3 |
| North Dakota | 13.2 |
| Northern Plains | |
| Cornbelt | 27.7 |
| Lake States | 23.4 |
| Southeast | 50.7 |
| Delta | 7.8 |
| Southern Plains | 6.5 |

Source: No-Till Farmer, March 1979.

It appears that the available data support a positive answer to the first question posed above: the present regional distribution of conservation tillage is consistent with what the literature tells us about the factors affecting yields of conservation tillage relative to yields of conventional tillage. Given that, what can we say in answer to the second question--the role of economics in the future spread of conservation tillage?

With respect to costs, the competitive position of conservation tillage relative to conventional tillage probably will be strengthened somewhat if energy prices rise over the long term, as is now generally expected. However, the overall impact probably will not be large. Table 8 shows that differences in fuel costs are a small part of the total cost differences between the two technologies. Moreover, an increase in fuel costs is likely to trigger an increase also in pesticide costs since most pesticides are petroleum based. This would weaken the competitive position of conservation tillage. In the section on costs we assumed no difference between the two technologies with respect to fertilizer requirements, but if in fact conservation tillage requires more fertilizer, particularly nitrogen, to achieve comparable yields, as much of the literature suggests, rising energy prices would weaken the competitive position of conservation tillage on this score also.

On balance, we do not expect changes in resource requirements and costs to significantly alter the present competitive position of conservation tillage relative to conventional tillage over the long term. The small present advantage of conservation tillage is expected to remain, neither widening nor shrinking by much. So far as the future spread of the technology depends upon economics, therefore, factors affecting comparative yields are likely to be most important.

If the demand for U.S. crop production and trends in crop technology behave as projected in Crosson and Brubaker, it is likely that the erosion advantage of conservation tillage will favor the technology more strongly in the future than it probably has so far. The reason is that under the projected conditions of crop demand and technology the demand for cropland would increase by 75 to 100 million acres from 1979 to 2010, and much of that additional land would be more erosive than land now in crop production.[21] The negative effects of erosion on the yields of such land likely would be more pronounced than on present cropland and therefore of more immediate concern to the farmer. The use of conservation tillage on these marginal lands should appear attractive.

Comparison of the amount of land now in conservation tillage in the Cornbelt with the amount with potential for the technology, judging from soil characteristics, indicates substantial room for expansion (see Table 10). How much of the potential might be realized is impossible to say, but the table raises some questions in this regard. The small amount of land in conservation tillage in Ohio (8.0 percent when the potential is 47.5 percent) suggests either that one or both of the numbers is wrong or that something other than soil characteristics is limiting the spread of conservation tillage in Ohio. Judging from entries in the literature as much research on conservation tillage has been done in Ohio as in any other state and more

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[21] Much of any land converted to crops would come from class I-IV land now in pasture. The USDA's Natural Resources Inventory of 1977 shows that 63 percent of present pasture land in classes I-IV has an erosion hazard. The comparable figure for present cropland is 50 percent.

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than in most.[22] It is hard to believe that the failure of conservation tillage to be more widely adopted in Ohio is because farmers do not know enough about its advantages. A more plausible alternative explanation (if we accept the numbers) is that for some reason weed control with herbicides is especially difficult in Ohio. That problems of weed control may be the principal obstacle to further spread of conservation tillage, not only in Ohio but elsewhere in the Cornbelt, is supported by the assertion of Pope, Downs, and Shurtleff, noted earlier, that weed control is the main factor limiting further adoption of conservation tillage in Illinois.

We already have suggested that the problem of controlling weeds, particularly perennials, in cotton is the main reason for the small amounts of land in conservation tillage in the Mississippi Delta and the Southern Plains. If weed control is also the principal limiting factor in the Cornbelt, then it would be fair to say that for the country as a whole the future expansion of conservation tillage depends more on improved techniques for controlling weeds, particularly perennials, than on any other single development. What is needed are new chemicals that would be effective against these weeds as well as new techniques of herbicide application. Much research and development now is under way to meet both of these needs. In Ohio, for example, promising experimental results have been obtained with post-emergence herbicides for control of both perennial and annual grasses in soybeans. It is expected that these materials will also be effective in dealing with perennials in a corn-soybean rotation. The grasses controlled include both Johnson grass and Bermuda grass. Techniques for post-emergence application of contact herbicides (ropewick devices) also are being developed in Ohio and elsewhere (G. B. Triplett, personal communication).

We expect efforts to develop new herbicides and techniques for applying them to receive additional impetus because of the value of conservation tillage in containing the erosion threat posed by the expansion of agricultural production onto marginal lands. Consequently we expect that present limits imposed by weed problems to the spread of conservation tillage will be pushed back. We defer specific estimates of the amount of additional expansion, however, until after consideration of relative environmental impacts of conservation and conventional tillage.

## ENVIRONMENTAL IMPACTS OF CONSERVATION TILLAGE AND CONVENTIONAL TILLAGE

The objective of the discussion is to reach judgments about differences between the two technologies with respect to environmental damages from erosion and from pollution by pesticides and fertilizers.

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[22] G. B. Triplett and his colleagues at the Ohio Agricultural Research and Development Center at Wooster have been researching conservation tillage for years and have published their results widely.

## EROSION

Erosion imposes environmental costs both on the farm and off the farm. On-the-farm costs are socially undesirable losses of productivity resulting from erosion of topsoil. Note that erosion-induced losses of productivity *per se* do not impose on-farm environmental costs. Only those losses which impinge on society's interest in the productivity of the land are counted. These losses arise when there is a divergence between the farmer's interest and society's interest in maintaining the productivity of the land. Society's interest includes those of future generations, but it is difficult for these interests to be registered in ways that will make the farmer responsive to them. As noted in the earlier discussion of the long-term effect of erosion on productivity, the farmer's concern about erosion is strongly conditioned by his expectations about future crop prices relative to current prices. Experience has taught American farmers to expect unstable prices. Consequently the prudent farmer likely will apply a high rate of discount to future prices, thus shortening his planning horizon. If current prices are high by recent standards, he likely will farm his land intensively, give less weight to soil conservation practices, and cause more erosion than is consistent with society's long-run interest in maintaining the productivity of the land.

If futures markets provided reliable estimates of prices in the distant future, these prices would provide farmers signals to guide their current land use decisions in a socially efficient manner. If these decisions promised long-term losses in productivity of the land, distant future prices would be high relative to current prices, thus increasing the present value of land-conserving practices and giving farmers incentive to adopt them.

Futures markets, of course, do not register prices expected to prevail generations into the future. The reason is not simply that those who will people future generations are not yet born or are too young to express their interests. In addition to this there is vast uncertainty about the interest of future generations in conserving the land and about how best to serve their interest, even if it were clearly identified. What will be the demands of future generations for products of the land, and how can those demands be modified, without damage to welfare, if they appear to exceed the capacity of the land to meet them? What are the possibilities that technological advances, e.g. higher yielding seed varieties, increased photosynthetic efficiency, hydroponic farming, will substitute for the land in meeting these demands?

If the uncertainty about the interest of future generations in maintaining the productivity of the land is so great, how can we be sure that there is a conflict between the social interest and the farmer's interest in the land? The fact is that we cannot be sure. We can be reasonably sure, however, that the combination of rising world population and income will substantially increase future demands for products of the land, that continued erosion over the long term will diminish the capacity of the land to meet the demands, that technological advance may or may not offset the decline in the land's capacity, and that if it does not the resulting increase in cost of the products of the land, food in particular, may produce significant social problems in the United States and elsewhere in the world where U.S. interests are involved. We can be more than reasonably sure that should this happen the rise in food prices would not be signaled to the farmer far enough in advance to induce him to take action to reduce erosion. It appears, therefore, that the prudent course for the society is to assume that there may be a divergence between the social interest and the farmer's interest in reducing erosion to maintain the productive capacity of the land.

Off-the-farm costs of erosion--impaired water quality with resultant damage to recreational values and aquatic life, accelerated siltation of reservoirs and harbors, increased flooding, health and esthetic damages from dust in the air--are more immediate and more evident than on-the-farm costs. Like on-the-farm costs, however, off-the-farm costs of erosion are not properly reflected in the farmer's management decisions because he does not bear them. There are no reliable estimates of the magnitude on a national scale of these off-the-farm costs of erosion, but the available evidence suggests that they are substantial.[23]

The literature leaves no doubt that erosion by both wind and water is much less with conservation tillage than with conventional tillage. The fundamental reason is that the residue left on the soil surface with conservation tillage reduces the impact of the energy of wind and water on the soil. In the case of water, the residue reduces both raindrop impact on the soil and velocity of run-off, thus reducing soil detachability and transport (Wischmeier). In the case of wind the residue absorbs much of the wind's energy (Woodruff and Siddoway). Conservation tillage typically leaves larger soil clods than conventional tillage and this too reduces both wind and water erosion. However, the surface residue is the key factor.

Soil ✓

In experiments Wischmeier found that soil lost to water erosion was inversely related to the percentage of the soil surface covered by residue. He also found that surface cover was far more important than any other factor in reducing erosion with conservation tillage relative to conventional tillage. For example, with various conservation tillage systems, including no-till, and 50 percent of the soil surface covered, erosion on corn without canopy was 19 percent to 24 percent of what it would have been with conventional tillage. The surface cover was responsible for 85 to 90 percent of the reduction in erosion.[24] With maximum canopy effect, erosion was 13 to

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[23] Pimentel et al. cite various sources estimating the cost of dredging sediment from rivers and harbors in the United States at $250 million annually, with siltation of reservoirs and other sediment damages bringing the total to $500 million. These figures relate to the 1960s and would be much higher in 1980 prices. Estimates of the contribution of cropland to total sediment vary, with most putting the figure at half, or somewhat more (Pimentel et al., Meister et al.).

[24] Calculated from data in Wischmeier, Table 3, p. 139. The other factors tending to reduce erosion in Wischmeier's experiments were amount of residue incorporated, soil detachability, soil roughness, and amount of corn canopy.

Work done in Ohio suggests that the erosion reducing effects of no-tillage are even more pronounced than Wischmeier's data indicate (G. B. Triplett, personal communication).

17 percent of what it would have been with conventional tillage, with soil cover accounting for 79 to 82 percent of the reduction. With more than 50 percent of the surface covered the contribution of residue to reduced erosion was more marked, and with a smaller percentage it was less. In all of the experiments conducted by Wischmeier, however, surface residue significantly reduced erosion and in all cases was the major factor in doing this.

Wischmeier's findings are generally consistent with those found throughout the literature with respect to both the effect of conservation tillage in reducing erosion and the key role of surface residue. Griffith, Mannering, and Moldenhauer cite simulated rainfall studies in Illinois and Indiana showing that chisel, till-plant and no-till systems reduced soil loss by 94, 60 and 95 percent respectively compared to conventional tillage after a high intensity storm. Ameniya cites studies in Iowa and Nebraska indicating that various kinds of conservation tillage reduced erosion 30 to 90 percent compared to conventional tillage. This range is the widest we found in our review of the literature. The great majority of studies show that conservation tillage reduces erosion by 50 to 90 percent compared to conventional tillage, with the percentage of surface covered by residue by far the most important factor in determining the amount of the reduction.[25]

Illinois ✓

## FERTILIZER

The principal concerns about fertilizers in the environment have to do with effects of nitrogen in water on human and animal health and of nitrogen and phosphorus in accelerating eutrophication of water bodies by stimulating growth of aquatic plants. There also is some evidence of damage to the earth's ozone shield from nitric oxide and nitrogen dioxide formed by decomposition of nitrous oxide released by denitrification.

Nitrates in water may constitute a hazard to both humans and animals that drink the water, not because the nitrates themselves are particularly toxic but because of their potential for conversion to nitrites which are toxic, or can be in sufficient concentration. Babies are more likely to suffer from nitrite poisoning than adults. Deaths and illnesses among farm animals also have been attributed to nitrite intoxication (Luhrs). Nitrogen gas dissolved in water or nitrogen in ammonia may kill or injure fish (Patrick).

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[25] A sampling of the literature with data about erosion effects of various tillage systems is USDA (May 1975); Fenster; Fenster and McCalla; Reicosky et al.; R. E. Phillips et al.; Harrold, Triplett and Edwards; Siemens and Oschwald; Siemens et al.; University of Illinois; Mannering and Burwell; Oschwald and Siemens. R. E. Phillips et al. conclude their discussion of the differences between conventional and conservation tillage with respect to erosion with the statement that "By far the most acceptable and effective measure for control of wind and water erosion is the maintenance of surface residues (mulches)" (p. 1109).

Eutrophication is a process involving the nutrient enrichment of lakes and reservoirs, the resultant growth of plant life, and the subsequent decline in the water's dissolved oxygen supply because of the oxygen demand of decaying plants. If severe, eutrophication makes the water incapable of supporting fish and spoils its value for some kinds of recreation. Eutrophication is a natural process, but it can be accelerated by the addition of nutrients supplied by man, including nitrogen and phosphorus carried by runoff water and soil eroded from farmland.[26] The amounts of these nutrients may be very small yet have significant effects in stimulating growth of aquatic plants. According to Holt, Johnson, and McDowell, as little as 10 parts per billion (ppb) of phosphorus and 100 ppb of nitrogen are enough to support growth of undesirable amounts of aquatic plants.

Denitrification of nitrate-N releases nitrous oxides which, converted to nitric oxide and nitrogen dioxide, may attack the earth's ozone shield. The resulting increase in solar radiation reaching the earth's surface would increase the risk of skin cancer. This possibility received considerable popular attention in the mid-1970s, particularly after press reports of work done by Michael McElroy at Harvard. The evidence for the effect, or for its quantitative importance, never was very clear, and the issue has faded from public discussion.

The ozone problem aside, the environmental damages of fertilizers depend upon how much of them reach water bodies through runoff, sub-surface flow, erosion, and percolation, and the condition of the receiving medium. The last point is important. Much nitrogen may be washed into a reservoir but if phosphorus is the factor limiting plant growth the nitrogen causes no problem of eutrophication. Much nitrogen may percolate to groundwater, but if the concentration level remains below the maximum thought consistent with human health (10 ppm of nitrate-N according to the U.S. Public Health Service) the likelihood of environmental damage is small.

The farmer's choice between conservation tillage and conventioanl tillage typically is not affected by the condition of receiving water bodies. Consequently, in comparing the technologies with respect to environmental impacts of fertilizers, differences in the amount of fertilizers reaching water bodies through erosion, runoff, sub-surface flow, and percolation are what count.

A study (Barisas et al.) under experimental conditions in Iowa found that most of the nitrogen and phosphorus lost with both conventional and conservation tillage was carried with eroded soil. Because erosion was much less with conservation tillage, total losses of both nitrogen and phosphorus were substantially higher with conventional tillage. Barisas et al. cite a number of other studies which came to the same conclusion.

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[26] Municipal and industrial wastes also include nutrients which contribute to eutrophication.

Not all of the nutrients carried by eroded soil are available to support aquatic plant growth. Most of the nitrogen carried by soil is in the organic form and is not available until it is decomposed to the nitrate form through the process of mineralization. Mineralization occurs at varying rates, but over time it would release some of the nitrogen carried by sediment, making it available to support growth of aquatic plants. This is not discussed by Barisas et al., however. In considering the impact of nitrogen on water quality they deal only with nitrate carried by runoff water. As noted below, concentrations of nitrate in runoff water from conservation-tilled fields typically are higher than concentrations from conventionally-tilled fields. If the increased concentration is sufficiently high and one focuses only on nitrate in runoff one would conclude that conservation tillage poses a greater threat to water quality than conventional tillage. If one considers total nitrogen delivered to water bodies, however, and allows for the fact that some of that carried by soil will stimulate growth of aquatic plants, then the advantage of conservation tillage in reducing erosion may offset its disadvantage in runoff transported nitrate. The net outcome could mean that conservation tillage poses a lesser threat to water quality so far as eutrophication is concerned.

In the literature surveyed, however, discussions of nitrogen and eutrophication invariably put the emphasis on nitrate carried by runoff. Possibly the contribution of soil-transported nitrogen to eutrophication is insignificant relative to that of nitrates carried by water, although this is nowhere explicitly stated. In any event, in the balance of this discussion we follow the literature in focusing only on nitrate carried by runoff water while keeping in mind the caveat that this may overstate the contribution of conservation tillage to eutrophication relative to that of conventional tillage.

Some of the phosphorus carried by eroded soil is available to plants, but the amount is variable. Wauchope, McDowell, and Hagen cite a number of studies indicating that 5 to 40 percent of the phosphorus in sediment is available.

If the concentration of available phosphorus in eroded soil was the same for both conservation and conventional tillage, then losses of available phosphorus clearly would be less with conservation tillage. Barisas et al. found, however, that the concentration of available P in eroded soil was higher with conservation tillage, and there is much evidence that this is generally true (Johnson et al; Wauchope, McDowell, and Hagen).[27] Barisas et al. suggest that this occurs because of leaching of nutrients from crop residues left with conservation tillage and because fertilizers generally are not as much incorporated with conservation tillage as with conventional tillage. Wauchope, McDowell, and Hagen cite a number of studies supporting this explanation.

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[27] These studies also found higher concentrations of nitrogen in soil eroded from conservation-tilled fields.

Conceivably the concentration of available P in soil eroded from conservation-tilled fields could be enough higher than that from conventionally-tilled fields that total losses of available P would be higher with conservation tillage even though erosion were less. This was not the case, however, in the situation studied by Barisas et al. when the proportion of the soil surface covered by residue was at least one-third. Thompson et al. studied erosion, runoff, and nutrient loss with conventional tillage and two kinds of conservation tillage in six small research watersheds in western Iowa over a four-year period. They found that although the concentration of available P was about three times higher in soil eroded from conservation-tilled fields total loss of available P was generally less with conservation tillage because erosion was so much less. The only exception was in one year with one of the conservation tillage systems.

According to Wauchope, McDowell, and Hagen there is considerable evidence that concentrations of nitrate nitrogen, ammonia, and available P are higher in runoff from conservation-tilled fields than from conventionally-tilled fields. Barisas et al. found this also. They also found that total amounts of nitrate-N ammonia and available P were higher in run-off water from conservation tilled fields. Siemens and Oschwald also found more nitrate-N lost with conservation tillage, but that losses of available P were the same or less compared to conventional tillage. In contrast, Wauchope, McDowell and Hagen cite a study by Haith and Loehr which showed smaller total dissolved-N losses with conservation tillage than with conventional tillage. The Haith-Loehr study was a modeling exercise which simulated mean dissolved-N losses over a twenty-five-year period at three locations in New York, Iowa, and Georgia. Johnson et al. reported no significant differences among tillage practices with respect to concentrations of nitrate nitrogen and ammonia in runoff, but both concentrations of soluble P and total amounts lost were higher with conservation tillage. The reasons for increased concentrations of nutrients in runoff are the same as for the higher concentrations in eroded soil--leaching from crop residues and less incorporation of fertilizers.

Runoff usually is less with conservation tillage than with conventional tillage (Siemens and Oschwald; Ameniya; Johnson et al.; Onstad and Otterby). The reason is that the crop residues and rougher soil texture typically found with conservation tillage reduce the velocity of water flow, permitting more water to remain on the field. With respect to concentration of nutrients in receiving surface waters, the reduction in runoff from conservation-tilled fields may or may not offset the higher concentrations of nutrients in runoff. If total nutrient loss is greater with conservation tillage, then the nutrient content of receiving waters will be higher with conservation tillage than with conventional tillage. If nutrient loss is less with conservation tillage than with conventional tillage, the nutrient content of receiving waters may be either higher or lower with conservation tillage. It will be higher if conservation tillage reduces the nutrient content of the receiving waters proportionally less than it reduces the total amount of water. If conservation tillage reduces the nutrient content of the receiving waters proportionally more than it reduces the amount of water, then of course the nutrient content of the receiving waters will be less with conservation tillage. Both

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of these conditions are consistent with higher concentrations of nutrients in runoff from conservation-tilled fields.

Clearly, there is little basis for generalizing about the differences between conservation tillage and conventional tillage with respect to delivery of nutrients to surface water bodies. The higher concentrations of nutrients in runoff from conservation-tilled fields, and the findings of Barisas et al. and Siemens and Oschwald that conservation tillage delivers much nitrate-N (not just higher concentrations in runoff) suggest that conservation tillage is a bigger threat to water quality than conventional tillage. However, the results of other researchers do not show greater nitrate-N losses with conservation tillage, and the simulation study by Haith and Loehr showed less. The situation with respect to phosphorus also is not clear. Since some available phosphorus is carried by eroded soil, the advantage of conservation tillage with respect to erosion may be enought to offset its disadvantage with respect to runoff. In general the advantage of conservation tillage with respect to the total amount of available phosphorus delivered to water bodies will be greater (1) the greater the reduction in erosion; (2) the smaller the difference between conservation and conventional tillage in concentration of total P in sediment; (3) the greater the percentage of total P in sediment which is available; (4) the higher the sediment delivery ratio; (5) the smaller the difference between the two tillage systems in concentration of phosphorus in runoff. While erosion typically will be substantially less with conservation tillage and the concentration of available P in both sediment and runoff higher, the range of difference in these and the other variables is large. Consequently, in delivery of available phosphorus to water bodies it is not clear whether the advantage of conservation tillage with respect to erosion is sufficient to offset its disadvantages with respect to concentrations of available P in sediment and runoff. Wauchope, McDowell and Hagen make no general statement about this in their review of the literature on the issue, and we have found no such statements in other sources.

A number of sources in the literature assert that the leaching of ninitrates to groundwater likely will be greater with conservation tillage than with conventional tillage. We have found no sources that dispute this, although in much of the literature the issue is not discussed. Generally, the amount of leaching is greater the more humid the environment and the more coarse textured the soil. (Phosphorus, since it is strongly absorbed by soil, does not leach to groundwater in significant amounts.) The increased leaching of nitrates, where it occurs, is a result of reduced runoff and increased infiltration. The leached nitrate moves to groundwater through percolation and/or to surface waters through subsurface flow.[28]

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[28] On increased leaching of nitrates with conservation tillage see Moschler and Martens; R. E. Phillips et al.; Thomas et al.; Bennett. On subsurface flow see Holt, Johnson, and McDowell, pp. 149-150. Wauchope, McDowell, and Hagen cite sources to the effect that nitrate nitrogen percolates deeper with conservation tillage because of higher infiltration rates. They also note that in large watersheds subsurface flow can transport greater amounts of nitrate nitrogen to surface water than runoff. They do not indicate, however, that subsurface transport of nitrate nitrogen would be greater with conservation tillage than with conventional tillage.

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## PESTICIDES

Pesticides cause environmental damage when they injure or kill unintended targets among plants and animals, including people. The question considered here is whether conservation tillage and conventional tillage differ significantly with respect to the likelihood of damage to the environment from pesticides. We noted in the section on quantities of resources that conservation tillage typically uses more pesticides, particularly herbicides, than conventional tillage, and this alone suggests that conservation tillage may threaten greater pesticide damage to the environment. However, the difference between the two systems is not simply that conservation tillage requires more herbicides. Conventional tillage is possible without herbicides. Conservation tillage typically is not. The nature and severity of the environmental damages of herbicides, therefore, are crucial to the future of conservation tillage. Should these prove so threatening that the society decides to impose severe restrictions on use of herbicides conservation tillage would no longer be viable, regardless of its economic advantage to the farmer.

In the section on quantities of resources we noted that conservation tillage may also require more insecticides and fungicides per acre than conventional tillage. The evidence on this was less clear-cut, however, than for herbicides. Moreover, for reasons developed elsewhere (Crosson and Brubaker, Chapter 5), we expect changes in insect management practices for cotton and corn (which receive about 70 percent of all insecticides applied to crops) to reduce the amounts of insecticides applied, both in total and per acre of cropland. We expect a corresponding reduction also in the perceived environmental damages of insecticides. Consequently we do not here consider differences between conservation tillage and conventional tillage with respect to environmental impacts of insecticides.

### Movement in Runoff[29]

Most pesticides show a strong affinity for soil. Consequently pesticide concentrations in eroded soil are usually higher than in the associated runoff. Some of the most commonly used pesticides, with high toxicity to aquatic life--trifluralin, endrin, and toxaphene--are so tightly bound to the soil that a reduction in erosion reduces the amounts of these materials leaving the farmer's field. This is true also of the herbicide, paraquat. For other less insoluble pesticides the bulk of losses are in runoff, even though the concentration of these materials in sediment is higher than in runoff. The reason is that water, by weight, is much the greater part of water plus soil. For these more soluble pesticides tillage practices which reduce erosion but not runoff will not significantly reduce pesticide losses. However, as noted earlier, conservation tillage typically reduces runoff as well as erosion.[30] This is especially true of no-till, and Wauchope, McDowell, and Hagen assert that "...pesticide losses are essentially eliminated under these conditions" (p. 23).

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[29] The discussion of differences between conservation tillage and conventional tillage with respect to the movement of pesticides by soil and water in runoff draws heavily on Wauchope, McDowell, and Hagen, pp. 20-25.

In a four-year study of six small research watersheds in Iowa where the land was in continuous corn planted up and down the slope, Baker and Johnson obtained results generally consistent with those given by Wauchope, McDowell, and Hagen in their review. Baker and Johnson studied pesticide losses to erosion and runoff with conventional tillage and two conservation tillage systems, till-plant and ridge plant. These systems respectively left 3, 20, and 45 percent of the soil surface covered with residue from the previous year's corn crop. The insecticide used was fonofos and the herbicides were alachlor and atrazine or cyanazine. Baker and Johnson found that in one year losses of fonofos with the till-plant system were greater than with conventional tillage and that in another year losses of atrazine with the ridge plant system exceeded those with conventional tillage. With these exceptions losses of both the insecticide and the herbicides were less with conservation tillage than with conventional tillage. Fonofos adheres more tightly to the soil than the herbicides and the greater part of the losses of fonofos with conventional tillage and the till-plant system were through erosion. For the ridge-plant system the greater part of losses of fonofos was in runoff. For all three systems much the greater part of herbicide losses was in runoff water, even though the concentration of these materials was greater in eroded soil than in the water. The reason was that there was much more water than soil in the runoff.

Because all of the pesticides were strongly adsorbed to the soil most of these materials remained in the top 5 cm of the surface with little or none reaching as deep as 25 cm. This finding is consistent with the conclusion of Wauchope, McDowell, and Hagen about the leaching of pesticides. In Barnes et al., however, Wauchope notes that the herbicide picloram is both persistent and leachable, and has been found in deep-well water in two counties in Nebraska. Although the concentration was very low--a few parts per billion--it was sufficient to damage sugar beets and dry bean plants when the water was used for irrigation.

## Other Environmental Damages of Pesticides

The focus here is on herbicides, since the main difference between conservation tillage and conventional tillage with respect to pesticides is in the amount of herbicides used, and because conservation tillage typically cannot be practiced without herbicides.

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[30] Conservation tillage also increases infiltration of water. However, Wauchope, McDowell, and Hagen cite a number of studies to the effect that subsurface water contamination by leaching of pesticides is rare, observed only at concentrations of a few parts per billion or less.

## Herbicide Drift--

Herbicide drift sometimes damages neighboring crops, and it is plausible to believe that the risk of this is greater with conservation tillage simply because more herbicides are applied.

## Effects on Soil Microorganisms--

Concern also has been expressed about possible damage to soil microorganisms by extended application of herbicides. There is disagreement in the literature on this issue. Sommers and Biederbeck assert that "...the results of numerous laboratory and field studies have indicated that herbicides and insecticides, when applied at recommended field rates, generally exert no harmful effects on microbial populations in the soil and their biochemical activities...The only important bacterial processes in soil that can be partly inhibited by certain herbicides and insecticides applied at low application rates are nitrification and nitrogen fixation, but the suppressive effects are invariably temporary" (p. 96).

Greaves appears to be in at least partial agreement with Sommers and Biederbeck. Summarizing a number of studies of the effects of herbicides on soil microorganisms Greaves states that "While there is some evidence that changes in the soil microflora do occur following long-term use of herbicides, the data suggest that these changes do not necessarily result in significant changes in soil processes such as nitrogen transformation. Where processes do apparently change, this is generally ascribable to decreases in soil organic matter or to uptake of nutrients by surviving weeds" (p. 131).

Greaves goes on to state, however, that despite this conclusion there is no room for complacency. Most of the work on the problem has ignored the effects of herbicides on microorganisms living on roots, and it is well known that herbicides affect root morphology and therefore, potentially, these root-dwelling microorganisms. Greaves ends by noting that relatively little is known about the long-term side effects of herbicides and calls for more research.

Eijsackers and van der Drift sound a similar note. They assert that while field tests show that soil fauna recover quickly from the toxic effects of herbicides, the processes underlying this are not well understood and "extensive research" is needed (p. 169). von Rumker et al. state that most studies of the metabolism and degradation of herbicides have focused on effects of herbicide residues in the soil on following crops or other valuable vegetation. Consequently there is little information about other effects of herbicide residues in the soil or in other elements of the environment.

## Effects on Humans--

In general herbicides have low toxicity to people. Paraquat is an exception. According to Giere, Johnson, and Perkins a dose of 10 to 30 mg/kg is fatal to half the human population, and continual contact in dilutions of 1 to 200 can cause skin irritation and loss or deformation of fingernails.

A number of herbicides, including paraquat, are under suspicion of being carcinogenic or mutagenic. Giere, Johnson, and Perkins cite two studies, one of which raises a question about paraquat as a mutagen, and another which failed to find mutagenic activity. Chemical and Engineering News (April 11, 1980, p. 4) refers to studies in Europe indicating that 2,4,5-T and 2,4-D increase the risk of developing certain kinds of cancer. 2,4,5-T, the infamous "agent orange" herbicide used for defoliation in Vietnam, is thought by some to also produce birth defects and other reproductive abnormalities, and 2,4-D has been indicted in the press as the probable cause of miscarriages among women in Montana living in areas where 2,4-D was regularly used. According to Chemical and Engineering News, however, a study by the U.S. Government's National Toxicology Program of the effects of 2,4,5-T and 2,4-D on male mice found no significant effect on fertility, reproduction, germ cell toxicology or survival and development of the offspring of the exposed animals. In any case, 2,4,5-T is no longer used on field crops, so the problems with it have no bearing on future choices between conventional and conservation tillage.

Atrazine, which accounts for almost 25 percent of all herbicides applied to crops in the United States, most of it on corn, has low toxicity to humans. There is evidence, however, that atrazine may be transformed metabolically by plants to form a substance which is mutagenic (Plewa and Gentile). Giere, Johnson, and Perkins assert further that atrazine can be transformed in the human stomach to a nitrogen derivative which is under strong suspicion as a carcinogen.

A study by M. J. S. Hsia of propanil, another low toxicity herbicide used on rice, showed that in the soil propanil is metabolized by first fungi and then microorganisms to a compound very similar to dioxin, the teratogen found in Agent Orange (Science News).

Finally, there is increasing concern about the effects of chemicals on the people engaged in manufacturing them, and herbicides are unlikely to escape scrutiny in this respect. In fact the International Chemical Workers Union has charged that Oryzalin, a herbicide made by Eli Lilly and Company for use mostly on soybeans and fruit crops, was responsible for birth defects or miscarriages among the children of five male workers at one of Lilly's plants (Chemical and Engineering News, Feb. 11, 1980, p. 28). Both the Occupational Safety and Health Administration and the National Institute for Occupational Safety and Health were looking into the union's charges against Oryzalin, without definitive results as of February, 1980. Whatever the outcome in this particular case, however, it probably is a harbinger of things to come.

## SUMMARY OF ENVIRONMENTAL IMPACTS

Erosion is much less with conservation tillage, giving it a clear advantage over conventional tillage with respect to both on-farm and off-farm impacts of erosion on the environment.

Losses of nitrate nitrogen in runoff, subsurface flow and percolation to groundwater probably are greater with conservation tillage. The amount of available phosphorus transported to water bodies by eroded soil will be less with conservation tillage, but the amount transported by runoff water likely will be more. The net outcome of these conflicting tendencies no doubt will vary from place to place and from time to time. No general conclusion appears warranted.

Losses of pesticides by eroded soil and runoff water generally are less with conservation tillage, and there is little leaching of pesticides to groundwater because most of them adhere strongly to the soil.

Herbicide drift sometimes damages crops in neighboring fields, and this is likely to be more of a problem with conservation tillage because it uses more herbicides than conventional tillage.

Such studies as have been done of the effect of prolonged use of herbicides on soil microorganisms indicate that the damages if any are slight, and the organisms recover quickly. However the studies have not covered all possible effects on soil organisms, so a final judgment should be withheld pending further research.

With few exceptions herbicides have low toxicity to humans. There is some evidence, however, that some of them may be carcinogenic, mutagenic or tertogenic, or that their metabolites may have these characteristics.

On balance, the increased reliance of conservation tillage on pesticides, particularly herbicides, makes it a greater threat to the environment than conventional tillage so far as pesticide damage is concerned.

The effect on the spread of conservation tillage relative to conventional tillage of their differing impacts on the environment will depend on how the society perceives and weighs these impacts. The tradeoff presented by conservation tillage between lower erosion damages and the threat of higher pesticide damages will be crucial. We discuss this in the next section.

## ECONOMIC AND ENVIRONMENTAL FACTORS IN THE FUTURE SPREAD OF CONSERVATION TILLAGE

### ECONOMICS

In the section on economics we concluded that problems of weed control with herbicides probably limit the continued spread of conservation tillage more than any other single factor. We also stated our belief that increasing

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demand for cropland will push farmers to convert more fragile land to crops, and that this will strengthen incentives to develop more effective herbicides to permit the continued spread of conservation tillage. Accordingly, without pretending that we have a solid base for it, we believe that economic factors could easily induce farmers to adopt conservation tillage on 50 to 60 percent of the nation's cropland by 2010. (In 1979 a little less than 25 percent of cropland was in conservation tillage—see Table 2).[31]

## THE ENVIRONMENT

If this does not happen it most likely will be because the society decides that the environmental threats of increased herbicide use with conservation tillage require that its spread be more restricted than the private economic calculations of farmers alone would indicate. To form a judgment about the likelihood of such restrictions we must consider the importance of threats to the environment from erosion and from the use of chemicals, particularly herbicides, with conservation tillage and with conventional tillage.

### Erosion

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Judging from statements by or in the name of private individuals and institutions as well as by public officials, erosion already is considered a serious threat to the environment, both on-farm and off-farm.[32] Partially in response to this concern, Congress passed the Soil and Water Resources Conservation Act in 1977 calling for an appraisal of emerging pressures on the nation's land and water resources, with special attention to the prospect for erosion from cropland. A review draft of this appraisal (RCA) was published in the spring of 1980 (USDA, 1980).

The National Resources Inventory (NRI) (Soil Conservation Service, February 1980) estimated that at present average annual erosion from cropland by water is 1.9 billion tons, or 4.7 tons per acre. Another 890 million tons

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[31] Crop residues can be used as feedstock to produce energy, either as alcohol or for direct combustion. There is much current discussion of the economic feasibility and social desirability of using crop residues and other other sources of biomass for this purpose. Should this path be taken, without heed to the erosion and fertility consequences of stripping the land of crop residues, the spread of conservation tillage would be checked, or even pushed back. We do not expect this to happen, however.

[32] See for example the Foreword by Lyle Bauer, President of the National Association of Conservation Districts, and various papers in Soil Conservation Society of America (1979); also the speech by Secretary of Agriculture Bob Bergland at a joint meeting of the Iowa Association of Conservation District Commissioners and the Iowa Association of Farmer Elected Committeemen, Aug. 18, 1980, Des Moines, Iowa.

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are lost annually to wind erosion in the ten Great Plains states.[33] Per acre losses from cropland to wind and water erosion combined are 6.8 tons per year. Per acre losses by region vary widely around the national average, from a high of 15.0 tons in the Southern Plains (primarily to wind erosion in Texas) to 1.4 tons on the Pacific Coast. Losses in the Cornbelt are 7.7 tons. The Soil Conservation Service (SCS) estimates that per acre losses of roughly 2 to 5 tons per year are consistent with indefinite maintenance of the productivity of the soil, depending upon the annual rate of soil regeneration.[34]

soil ✓

Evidently continuation of present amounts of erosion will eventually reduce the productivity of the nation's cropland, in addition to imposing annual off-farm costs. How serious are these present and prospective costs? For off-farm costs we have no estimates other than those given in the earlier section on erosion. For on-farm costs--the loss in soil productivity--the USDA estimates in the RCA that continuation of 1977 rates of erosion for fifty years would reduce the nation's capacity to produce crops the equivalent of 23 million acres. More to the point, the costs of food and fiber would be almost double what they would be if farmers reduce erosion by adopting conservation tillage in response to its economic advantages (USDA 1980, p. 3-39).

Projections made by Crosson and Brubaker of the growth in crop production and yields imply that erosion by 2010 would be higher than in 1977, even if conservation tillage continues to spread. Table 12 shows this. As indicated in the table note on sources, the projections of cropland by tillage system and of total erosion are from Iowa State University's model of U.S. agriculture. The alternative 1 projection was constrained with respect to the regional location of production but not with respect to tillage system. The alternative 2 projection was not constrained by region, so the model chose a regional distribution which permitted the same output with less land. Alternative 2 was constrained, however, in choice of high conservation tillage in the Cornbelt and Northern Plains on the basis of our earlier analysis of yield factors limiting the spread of conservation tillage.

The Iowa State model incorporates the long-term effects of erosion on yields. Hence over the long term it strongly favors conservation tillage. Whether farmers would take the same long-term view and actually adopt conservation tillage on the scale indicated in Table 12 is questionable. We return to this below.

The alternative 1 projection indicates that sheet and rill erosion per acre of cropland would be the same as in 1977--4.7 tons. However, total erosion would be 22 percent higher. This suggests that off-farm costs of erosion in the form of impaired water quality would be higher in 2010 than at present.

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[33] Average per acre loss to wind erosion in these states was 5.3 tons per year (USDA, Aug. 21, 1979). According to the NRI, these states had 168.5 million acres of cropland in 1977.

[34] Five tons of soil is about .033 acre inches.

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## TABLE 12. PROJECTIONS OF CROPLAND AND EROSION IN THE UNITED STATES IN 2010

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| Cropland in millions of acres | (1) Alternative 1 | (2) Alternative 2 |
|---|---|---|
| Cropland by tillage system | 444.9 | 427.6 |
| High conservation till[a] | 213.4 | 131.6 |
| Medium conservation till[b] | 155.1 | 223.2 |
| Conventional till | 76.4 | 72.8 |
| Other cropland | 48.1 | 48.1 |
| Total cropland | 493.0 | 475.7 |
| Total sheet and rill erosion (millions of tons)[c] | 2,320 | 3,537 |
| Sheet and rill erosion per acre (tons) | 4.7 | 7.4 |

[a] Surface residue left year around and no moldboard plowing.

[b] Residue left from harvest to spring planting when the moldboard plow may or may not be used.

[c] Sheet erosion is the movement by water of continuous layers of soil from the field. If the water moves fast enough it scours the soil and cuts small channels in the soil surface. The soil moved in this fashion is rill erosion.

Source: Cropland by tillage system and total erosion from Iowa State University's model of U.S. agriculture, using projections of production and yields provided by the author. Differences in amounts of land by tillage system are explained in the text. Other cropland is 18.1 million acres not allocated by tillage systems in the Iowa State model, 20 million acres of idle land, and 10 million acres on which crops are lost. The 20 million and 10 million acre estimates are based on long experience in the United States. The idle land is not part of a reserve. Rather it is land not used for a wide variety of reasons. Erosion is by water only.

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Alternative 2 shows substantially more erosion, both in total and per acre, than at present, even though the amount of cropland is less than in alternative 1. The reason is that the Iowa State model was not free to put as much land in high conservation tillage in the Cornbelt and Northern Plains as in alternative 1. There was no constraint on choice of medium conservation tillage, however, so the model opted strongly for that, leaving land in conventional tillage about the same as in alternative 1. Erosion nonetheless is higher than in alternative 1 because medium conservation tillage is less effective in reducing erosion than high conservation tillage.

With alternative 2 both on-farm and off-farm costs of erosion would be substantially higher than at present.

Judging from the RCA report continuation of present rates of erosion would over the long term exact high costs in lost productivity of the land (see p. 91 above). It is important to note that the high levels of erosion in alternatives 1 and 2 occur even though most cropland in 2010 would be under some form of conservation tillage. If steps were taken to limit the spread of conservation tillage out of concern about the effects on the environment of increased use of chemicals, particularly herbicides, erosion would be greater than depicted in alternatives 1 and 2, and its costs, of course, also would be higher. Are the environmental costs of conservation tillage on account of herbicides likely to be so high that the society would restrict its spread despite the higher costs of erosion this would entail? We do not pretend to be able to give a firm answer to this question. Still the question must be addressed if we are to reach a judgment about the future spread of conservation tillage.[35]

## Chemicals

We concluded above that the evidence does not support firm conclusions about differences between conservation tillage and conventional tillage with respect to delivery of nitrates and available phosphorus to water bodies. We have no basis, therefore, for judging whether the shift to conservation tillage would increase or decrease nitrate and phosphorus contamination of water. Although the amounts of nitrogen and phosphorus fertilizers used by American farmers are likely to increase significantly over the next several decades, possibly increasing the threat to water quality (Crosson and Brubaker), it is not clear that farmers' choices between conservation tillage and conventional tillage will significantly affect the magnitude of the threat.

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[35] The discussion of environmental impacts assumes that production and crop yields will grow as projected by Crosson and Brubaker. Should production grow more slowly or yields more rapidly, the demand for cropland would not be as great as shown in Table 12 and erosion would be less. Consequently the social cost of limiting the spread of conservation tillage would be less. It also is possible that if a situation like that shown in Table 12 were to emerge the society would take steps to limit the expansion of exports so as to reduce pressure on the land. This, of course, would involve trading off higher costs in foregone production against lower costs of erosion.

The situation is different with respect to herbicides since conservation tillage typically requires more herbicides per acre than conventional tillage. The question we address is whether the increased threat of herbicides to the environment posed by the spread of conservation tillage will be judged by the society to be more or less serious than the greater environmental damages from erosion which likely will occur if the spread of conservation tillage is restrained by social sanctions.

Our review in the previous section of the environmental damages of herbicides provides little evidence that present levels of use of herbicides pose a major threat to the environment. This judgment is supported by a survey of thirty-six agricultural scientists from all around the country (Barnes et al.).[36] The scientists were asked to describe cases of water pollution by pesticides which in their judgment constituted a problem. Only two problems clearly involving farm-applied herbicides were listed. Both were crop damage resulting from use of herbicide-contaminated water for irrigation. Picloran, a particularly persistent and leachable herbicide, has been found in the water of wells in two counties in Nebraska. The concentration was only a few parts per billion, but was enough to damage crops irrigated with the well water. Similar damage was reported in cases where water from a pond contaminated by herbicides in runoff was used for irrigation, and where herbicides-contaminated runoff flows directly into fields.

The survey also brought mention of possible damage from atrazine and alachlor residues in sediment in the Chesapeake Bay estuary and in the Bay itself. A study suggested that these residues were killing bottom vegetation in the Bay. This is in dispute, however, because the scientific procedures used in the study are believed by some to be inadequate.

R. D. Wauchope, the person responsible for the survey of expert opinion about present pesticide damages to water quality, summed up his findings as follows:

> It is unlikely that any significant observable, nonpoint source water quality problem due to proper agricultural or silvicultural use of pesticides would not be known to at least one of the sources [interviewed]...It is a reasonable conclusion, then, that with a few possible exceptions, currently-registered agricultural and silvicultural pesticides are not observed to be causing problems with respect to water quality (Barnes et al., p. 15. Emphasis in the original).

It does not follow, however, that there is no cause for concern about present levels of herbicide use or about the much higher levels of use that inevitably would accompany the continued expansion of land in crops and a rising proportion of it in conservation tillage. In the first place, the experts surveyed by Wauchope did not address the possibilities that some herbicides, as noted in the previous section, may be carcinogens, mutagens or teratogens. In the second place, the absence of evidence that herbicides now constitute a major environmental threat may simply reflect the failure of researchers to look in the right places, or the inability of present detection techniques to pick up effects at very low trophic levels. We noted in the previous section, for example, that researchers studying the effects of herbicides on soil microorganisms commonly emphasize the paucity of knowledge in this area and the need for more research. Moreover, much of the research on herbicides has focused on the environmental effects of the materials themselves. Much less has been concerned with the effects of their metabolites. The research of Plewa and Gentile on atrazine and of Hsia (Science News) on propanil, mentioned in the previous section, indicates that metabolic products may cause environmental damage even when the original material does not.

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[36] The survey was conducted by R. D. Wauchope in 1979.

soil ✓

There is, therefore, no ground for complacency about the higher levels of herbicide use that would accompany the spread of conservation tillage. There is even less ground for complacency, however, about the increase in erosion that likely will occur if conservation tillage is not permitted to spread. The evidence is strong that over the next several decades erosion may exact high social costs even if conservation tillage spreads widely. This is the implication of Table 12. If conservation tillage is not permitted to spread these costs will be higher still. In contrast, present evidence that higher levels of herbicide use would impose social costs comparable to those of erosion is weak.

We believe that on the present evidence the society should actively support the spread of conservation tillage. Indeed, this already is happening. The Soil Conservation Service and private groups interested in soil conservation long have encouraged farmers to adopt conservation tillage. Heretofore, however, this encouragement has lacked financial backing. Now the Congress has provided funding under the Clean Water Act that can be used to give farmers financial incentives to adopt conservation tillage. By so doing the Congress, and associated government agencies--the SCS, the EPA, and state conservation agencies--explicitly recognize that erosion presents a water quality problem as well as a soil productivity problem.

At the same time that the federal government is actively supporting the spread of conservation tillage as an erosion control measure it also, through the EPA, is taking steps that could limit spread. We refer of course to requirements that herbicides pass close scrutiny with respect to their environmental damages before they may be used. There is no inconsistency in this. The danger of erosion is not so "clear and present" as to override all concern about possible environmental damages of herbicides. In fact our very lack of knowledge about the more subtle and longer-term effects of herbicides is the strongest reason for pursuing a policy of hard-eyed scrutiny of these materials, even if this slows somewhat the spread of conservation tillage.

## CONCLUSION ON THE FUTURE SPREAD OF CONSERVATION TILLAGE

At the beginning of this section we stated our belief that economic factors would support the spread of conservation tillage to 50 or 60 percent of the nation's cropland by 2010. On the present evidence about the environmental costs and benefits of conservation tillage we believe the society will actively encourage this spread.

But why should we not expect conservation tillage to occupy 75 percent of cropland, as the Iowa State Model's projections indicate? (Table 12). We take a more conservative position because we believe farmers are unlikely to take as long a view of the effects of erosion on yields as does the Iowa State model. However, our position does not allow for a major expansion of government funding to encourage the development and spread of conservation tillage. If a situation like that depicted in Table 12, particularly alternative 2, begins to emerge, the threat of erosion damages may spur a greatly increased government effort in support of conservation tillage. We consider such an outcome not improbable. Consequently our judgment that conservation tillage will spread to 50 or 60 percent of the nation's cropland is conservative.

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